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Graphene Fibers and Modern Solar Textiles: A Review of Advances and Applications

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This review critically analyzes the transformative role of graphene fibers (GFs) in advancing photovoltaic textiles. Our key findings reveal that GFs enable a multi-functional architecture, serving simultaneously as conductive electrodes (sheet resistance ~ 600 Ohms per square), charge transport layers, and structural scaffolds, which enhances mechanical durability under stress. We identify that GF integration significantly boosts device performance and stability, achieving record efficiencies of 33.28 % in CIGS / GO hybrids and extending perovskite device lifetime by 91 %. Furthermore, our analysis of 290 studies demonstrates that GF-based textiles maintain 90% efficiency across extreme temperatures (-40°C to 160 °C). However, a critical barrier to commercialization is the high embedded energy in GF fabrication. We conclude that overcoming interfacial resistance and scaling production through doped GF networks and AI-assisted manufacturing are the most urgent priorities for creating viable, high-performance solar textiles for wearable electronics and sustainable energy.

1. Introduction

Carbon nanotubes (CNTs) have significantly advanced global nanotechnology research. Graphene oxide (GO) serves as a fundamental building block for many carbon nanomaterials, including graphene quantum dots (GQDs), CNTs, fullerenes, and graphene nanoribbons [1]. This breakthrough laid the groundwork for subsequent graphene research, establishing it as a transformative material in solar textiles. Graphene-based materials have attracted significant attention as potential replacements for conventional materials in photovoltaic (PV) devices. However, realizing their full potential requires

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precise control over synthesis to achieve optimal structure-property relationships for enhanced device performance [٢]. For instance, insulating textile fibers can be transformed into conductive ones via graphene coating, achieving sheet resistances as low as 600 Ohms per square. This method is applicable across various fiber types and sizes, and graphene forms, enabling integrated e-textile devices with excellent conductivity retention [3]. Electricity, primarily sourced from non-renewable fossil fuels (79.5%), dominates modern energy systems **[**4**]**. PV generated 830,741 GWh in 2020 and accounted for 60% of global renewable energy investments by 2022. Photovoltaic cells (PVCs) are categorized into three generations:

1. **First-generation**: Multi-crystalline silicon homogeneous junction cells,
2. **Second-generation**: Thin-film compound semiconductor hetero-junction cells,
3. **Third-generation**: Advanced multi-junction, multi-semiconductor tandem cells [5**].**

Perovskite ($CaTiO_2$), first discovered in 1839 by Russian scientist Gustav Rose and later named after mineralogist Lev Perovski, is now enabling breakthroughs in solar cells, superconductivity, magneto-resistance, and microelectronics due to its versatile properties [6]. Understanding how structural variations influence electrochemical activity allows strategies from one system to be adapted for others [7]. For example, bio-inspired MXene/rGO/MoS_2 nano-coatings achieve 93.2% light absorption, enabling efficient solar steam generation (1.33 kg m^{-2} h^{-1}) and stretchable dual-powered heaters (more than 100°C) for advanced solar-thermal applications [8]. Notably, GQDs play a crucial role in enhancing hetero-junction solar cell efficiency **[9].** Solar-powered solutions improve industrial efficiency while reducing costs, a novel parabolic trough collector with a flat reflector against a standard model achieved a competitive 55% thermal efficiency and increased the working fluid's temperature by an average of 6.85°C, a 1.14°C improvement over the standard collector [10-12]. Ni and Li-doped ZnS nanoparticles were synthesized using green, surfactant-assisted methods. Doping effectively reduced the band gap, enhancing the material's photocatalytic properties. The nanoparticles successfully degraded multiple azo dyes under solar irradiation in under 120 minutes [13]. Figure 1 illustrates the key research topics and their interrelationships in this study. Notably, the structural differences among carbon nanomaterials significantly impact their electrochemical performance.

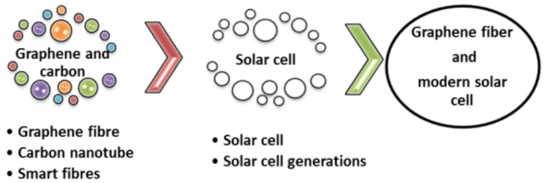

Figure 1. The research topics and the relationship between them

Despite these advances in smart nanomaterials, significant potential remains untapped, particularly in sophisticated functionalization and safety assessment. The long-term effects of exposure and safe implementation protocols require further exploration to unlock their full application potential [14]. This review comprehensively examines the transformative role of graphene-based materials in PV technologies, with a focus on solar textiles and perovskite solar cells (PSCs). It explores the structure-property relationships of graphene that enable its multifunctional applications, recent advancements in graphene-enhanced textile solar cells demonstrating superior conductivity and stability, and graphene's critical role in stabilizing perovskite structures while improving charge transport efficiency. It also addresses key challenges, including scalable production, interface optimization, and doping control. Furthermore, it provides design principles for developing next-generation PVs that achieve an optimal balance between efficiency, stability, and cost-effectiveness for sustainable renewable energy solutions.

2. Structured overview

2.1. Solar cell generations

PVCs have undergone a significant development since their inception, evolving through several generations characterized by advancements in materials and technology (Table 1). Solar PV technology can be classified into key generations based on the materials and manufacturing processes [15-17]:

- Monocrystalline silicon solar cells: These cells are made from highly pure silicon and are the most efficient but also the most expensive, with efficiencies of around 20% and warranties of up to 25 years.
- Polycrystalline solar cells: These are made of multiple silicon crystals and are less expensive and less efficient than monocrystalline cells.
- Thin-film solar cells: These are made by layering PV materials and include:

- Amorphous silicon, which is used for smaller applications.
- Cadmium telluride, with an efficiency levels of around 10%.
- Copper indium gallium selenide, which is still in the research phase.
- Organic PV cells.

- Emerging PVC technologies: These include perovskite solar cells (PSCs), organic solar cells (OSCs), dye-sensitized solar cells (DSSCs), and quantum dots (QDs).

Table 1. Main types of solar cells: market status, and research directions

Solar cell type	Current status and market share	Research directions
Crystalline Silicon (c-Si) [18, 19]	- Market share: ~84% of c-Si production (2023). - Efficiency: 20–26.7% (lab). - Lifespan: 25–30 years.	- Goal: Reduce cost via thinner wafers. - Focus: PERC+/TOPCon for >27% efficiency.
Amorphous Silicon (a-Si) [20, 21]	- Market share: ~11% of c-Si (lower cost). - Efficiency: 15–17% (commercial). - Declining due to mono-Si dominance.	- R&D: Passivation layers to mitigate grain-boundary losses.
CIGS/CdTe (Thin Film) [22, 23]	- Niche market: BIPV/flexible apps. - Efficiency: 7–12.7%. - Stability issues.	- Focus: a-SiGe alloys for IR absorption. - Hybrids: Tandem with perovskites.
Perovskite [23-25]	- Market share: ~5% (First Solar's leader) - Efficiency: 22.3% (lab), ~18% (modules). - Low-cost.	- Goal: Cd-free (e.g., ZnTe) for eco-friendliness. - Scalability: Faster deposition.
Organic (OPV) [26, 27]	- Efficiency: 23.6% (lab), ~19% (modules). - Limited commercialization.	- R&D: Flexible substrates (metal foils). - Ga grading for bandgap tuning.
Dye-Sensitized (DSSC) [28, 29]	- Lab efficiency: ~26% (single-junction). - Stability challenges (moisture/heat). - Tandem potential: 33.7% with Si.	- Scalability: Roll-to-roll printing. - Lead-free alternatives (Sn, Ge).
Graphene-Based [30, 31]	- Efficiency: 19.2% (lab). - Flexible/lightweight but short lifespan.	- Stability: Non-fullerene acceptors. - Indoor PV applications.
Metamaterials [32, 33]	- Efficiency: 15.2% (grätzel cell). - Low-light performance. - Niche uses: Portable electronics.	- Solid-state electrolytes for durability. - Cost reduction via Pt-free electrodes.
Crystalline Silicon (C-Si)[18, 19]	- Lab efficiency: ~18% (PbS QDs). - Theoretical potential: >30%.	- Toxicity: Pb-free QDs (e.g., $CuInSe_2$). - Multi-exciton generation.

2.2. Simulation and synthetic methods on solar cell

Solar photovoltaic capacity is projected to increase by 8 to 14 times by 2050, compared to its 2022 level. Solar energy is poised to dominate global electricity markets by 2050–2060, driven by its availability and cost-effectiveness, potentially marking an irreversible tipping point [34]. Table 2 shows some simulation methods for modeling data and technology diffusion trajectories. First-generation solar cells use monocrystalline silicon with about 20% efficiency and a cost of $0.30 per watt. Second-generation cells are thin-film CIGS with 10–15% efficiency and use flexible substrates. Third-generation cells include germanium-based KGeCl3 perovskite hybrids, which use TiO2 and Cu2O layers with graphene, achieving 31.13% an efficiency and eco-friendly stability [35]. C-Si (20-26.7%) benefits from high purity, doping, and PERC to maximize efficiency. Thin films like CIGS/CdTe (23.6%) use annealing for bandgap optimization, while perovskites (26%) achieve rapid progress through defect reduction, and organic cells (19.2%) enhance charge transport via morphology control [36]. Table 3 shows the developments in solar cell materials, summarizing how synthetic methods affect the performance of different solar cell materials, along with key references.

Synthesis Protocols for Graphene-Textile Integration (from Table 3):

1. Dip-Coated/Plated Yarns: Fabrication involves immersing textiles in GO solutions followed by chemical reduction or metal deposition, achieving 0.1-100 ohms per square conductivity, though with potential flexibility trade-offs.
2. Wet-Spun Graphene Fibers: GO dispersions are extruded into coagulation baths, producing aligned fiber structures with exceptional

mechanical strength (500 MPa) and electrical conductivity (10^3 S/cm).

Table 2. Simulation methods for data and technology diffusion trajectories

Method	Description	Advantages	Disadvantages
E3ME [37, 38]	A macro-econometric model covering 70 regions and 43 sectors, using input-output tables and bilateral trade. Links energy, economy, and employment up to 2070.	- Broad regional and sectoral coverage - Integrates economic and energy systems - Long-term projections	- Complex calibration - High computational demand - Limited granularity in tech diffusion
FTT Models [38, 39]	Evolutionary models simulating tech diffusion in power, transport, heating, and steel using cost comparisons and replicator dynamics. Includes 24 power technologies.	- Captures market competition - Detailed sectoral analysis - Grid stability insights	- Limited to selected sectors - Assumes rational cost-driven adoption - Less macroeconomic integration
FTT Power [40, 41]	Enhanced solar PV, wind, and storage (lithium-ion, hydrogen) modeling with learning curves, updated capacity factors, and technical potentials.	- Explicit learning curves - Improved storage dynamics - High-resolution tech detail	- Narrower sector focus - Relies on cost assumptions - Less macroeconomic feedback
E3ME-FTT-GENIE [42, 43]	Integrates economic, technological, and climate modeling across 43 sectors and 70 regions, combining energy markets with climate projections.	- Holistic system integration - Combines macroeconomics with tech diffusion - Climate policy assessment	- Extremely complex - High data requirements - Extended runtime for simulations

Table 3. Impact of synthetic methods on solar cell performance

Material/Type	Synthetic method	Impact on performance	Efficiency range %)
Crystalline silicon (c-Si) [18, 19]	Carbon reduction, doping (B, P), PERC/PERL passivation	Higher purity and passivation reduce recombination, improving Voc and FF. Texturing reduces reflection.	20–26.7 (mono-Si) 15–17 (poly-Si)
Amorphous silicon (a-Si) [20, 21]	Plasma-enhanced CVD (PECVD) with hydrogenation	H-passivation reduces dangling bonds, improving carrier lifetime. Ge/C alloying enhances IR absorption.	7–12.69
CIGS/cdte (Thin Film) [22, 23]	Physical vapor deposition (PVD), sputtering	Stoichiometry control (Cu/In/Ga ratio) and post-deposition annealing optimize bandgap and carrier collection.	22.3 (CdTe), 23.6 (CIGS)
Perovskite [23-25]	Solution processing (spin-coating), vacuum evaporation	Precursor composition (e.g., $Cs_{0.05}FA_{0.95}PbI_3$) and solvent engineering reduce defects, improving stability.	3.8 - 26 (2009–2023)
Organic (OPV) [26, 27]	Bulk heterojunction (BHJ) blending	Donor-acceptor nanoscale morphology optimization enhances exciton separation and charge transport.	Up to 19.2
Dye-sensitized (DSSC) [28, 29]	TiO_2 nanoparticle sintering + dye adsorption	Dye molecular engineering (e.g., N719 - LEG4/ADEKA-1) and redox couples ($Co^{3+/2+}$) boost Jsc.	Up to 15.2
Graphene-based [30, 31]	CVD growth, GO functionalization	High conductivity (550 S/cm) and transparency (70%) replace ITO. doping (GO-Cs) improves charge extraction.	~20 (enhancement)
Metamaterials [32, 33]	Nanofabrication (e.g., TiN, Pd nanostructures)	Broadband absorption (>98%) and light trapping overcome S-Q limit via geometric tuning.	Theoretical ~85 (STPV)

3. Woven Graphene Textiles: Conductive graphene fibers are integrated via industrial weaving processes, maintaining 1-50 Ohm per square conductivity while preserving textile properties through more than 50 wash cycles.
4. Printed Encapsulated Sensors: rGO/Ecoflex inks are screen-printed and polymer-encapsulated, creating ultra-sensitive (GF=10-3500), highly stretchable (300%) wearable sensors.
5. Biodegradable Composites: Solution-processed graphene/biopolymer blends demonstrate controlled degradation (0.5-2%/day) while maintaining 10^{-1}-10^{2} S/cm conductivity for sustainable applications.

2.3. Global trends

Silicon solar cells offer 20–25% efficiency with low flexibility and limited graphene integration. Perovskite-graphene hybrids provide 9–31% efficiency, high flexibility, and graphene use in electrodes or hole transport layers. DSSCs with CNT fibers achieve 6–8% efficiency, moderate flexibility, and graphene as counter electrodes (see Table 4). Recent advancements include carbon nanomaterial integration, perovskite commercialization, and 2D material hybrids systems. Innovations span flexible PV textiles, graphene fibers for wearable fiber solar cells (over 9% efficiency), and temperature-resilient perovskites (stable from -40°C to 160°C), addressing key challenges in transparency and scalability. Table 5 presents key developments in solar cell materials and technologies. Table 6 summarizes global trends in graphene-based solar technologies (2024–2025). Carbon nanomaterials (graphene, CNTs, fullerenes) offer low-cost, high-conductivity alternatives to noble metals, with solution processability and tunable work functions (~5.0 eV) [44]. Their superior electronic and mechanical properties enhance charge generation, transport, and collection in PVCs, significantly boosting solar cell efficiency [44].

Table 4. Solar cell types (Structured Comparison)

Type	Efficiency	Flexibility	Graphene Fiber Integration Potential
Si-based	20–25%	Low	Limited (scaffolds only)
Perovskite-GF hybrid	9–31%	High	Electrode/HTL[45]
dye-sensitized solar cells with CNT fibers	6–8%	Moderate	Counter electrode[46]

Table 5. Key developments in solar cell materials and technologies

Development	Description
Carbon nanomaterial integration [47]	Use of CNTs, buckyballs, and graphene for high-efficiency PVC
Perovskite commercialization [45]	Advances in PSCs for scalable production
2D material hybrids[48]	Solar cells combining graphene with molybdenum diselenide
Multifunctional graphene fibers[49]	GF integration with energy-harvesting/storage components
Carbon-perovskite-quantum dot systems[44]	Hybrid carbon-based cells using perovskites and QDs
Flexible PV textiles[50]	Development of textile-integrated PV materials
Mechanically robust GFs[51]	Graphene fibers enhancing solar cell durability and performance
CNT transparency limitations[52, 53]	CNT-based cells hindered by low optical transparency
Wearable fiber solar cells[54, 55]	Fiber-shaped solar cells woven into power-generating textiles
Self-powered e-textiles[56]	PV textiles for flexible wearable electronics
Nano-fiber enhanced PV[57].	Electrospun nanofibers boosting textile solar cell efficiency
Temperature-resilient perovskites[58]	Perovskite solar textiles maintaining efficiency (-40 °C to 160 °C)
High-efficiency fiber cells[59]	Flexible fiber-shaped solar cells achieving > 9% efficiency

Table 6. Global trends in graphene-based solar technologies (2024–2025)

Category	Key advancements	Performance metrics	Innovations
Heterojunction solar cells [9]	GQDs enhance Si heterojunctions	60% share of global renewable investments (2022)	Fragmented GQDs for photoluminescence. improved charge transport
PSCs [60]	Plasma-assisted graphene as HTL (ITO/PCBM/CsPbI3/graphene)	Efficiency linked to Debye length modulation	PECVD-grown graphene. SCAPS-1D modeling
DSSCs [61, 62]	Graphene-TiO_2 photoanodes. multilayer designs	Enhanced charge collection	Quasi-solid-state DSSCs. irradiance resilience
Solar thermal and absorbers [63, 64]	Graphene-paraffin PCMs. fractal metasurfaces. plasmonic absorbers	95–98% broadband absorption (200–3000 nm)	Machine learning-optimized designs. angle/polarization resilience
Nanofluids and heat transfer [65, 66]	Graphene-based ionanofluids in solar collectors/dryers	20–30% thermal efficiency boost	Hybrid PV-thermal systems. explosive-synthesized MgO/graphene nanocomposites
Schottky junction solar cells[67]	2D-graphene/3D-Si interfaces	Low-cost, scalable fabrication	Surface modification for reduced recombination
Photocatalysis and gas sensing [68, 69]	S-doped graphene for toxic gas sensing/solar sensitizers	DFT-validated eco-friendly designs	Core–shell Ni/SiO_2/graphene nanoparticles

3. Evolution of carbon nanomaterials

3.1 Carbon nanomaterials

In 1952, Radushkevich and Lukyanovich produced hollow circular carbon fibers with a diameter of 50 nanometers [70]. CNTs were first synthesized in 1991 (before graphene's isolation) using chemical vapor deposition. Later, scientists at Stanford University developed the first carbon-based solar cell [71]. Graphene is a single-layer, two-dimensional carbon allotrope arranged in a hexagonal lattice, where each carbon atom forms three bonds with its neighbors (This structure involves three sigma bonds and one pi bond per carbon atom). Composed entirely of carbon-12 atoms, it is essentially a single-atom-thick layer of graphite. Graphene has the potential to replace noble metal catalysts as a counter electrode. The strong covalent bonds between its carbon atoms give graphene exceptional tensile strength. Graphene’s unique structure grants it remarkable properties, including high mechanical strength, excellent thermal and electrical conductivity, and near-transparency. On the other hand, CNTs, on the other hand, are hollow carbon structures with nanometer-scale diameters. They consist of a well-ordered arrangement of carbon atoms linked by strong covalent bonds, exhibiting extraordinary properties such as high tensile strength and thermal conductivity [70, 72]. Their properties, including their mechanical strength, stem from the robust carbon-carbon bonds inherited from graphene. CNTs can be classified as single-walled (SWCNTs) or multi-walled (MWCNTs). SWCNTs can adopt different configurations—armchair, chiral, and zigzag— which influence their electronic and optical properties. The electronic properties of single-walled carbon nanotubes (SWCNTs) vary significantly based on their atomic structure. Armchair configurations demonstrate exhibit metallic characteristics, whereas zigzag tubes exhibit semiconducting behavior [73]. Structurally, SWCNTs are formed by rolling a graphene sheet into cylindrical shape, while multi-walled nanotubes (MWCNTs) comprise multiple concentric graphene layers, as illustrated in Figure 2 [7].

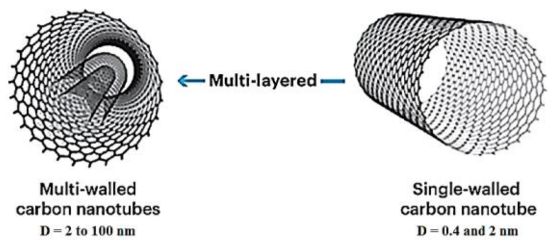

Figure 2. The two types of CNTs[7].

Table 7 presents a timeline highlighting key milestones in the development of CNTs, graphene, and composite materials. The period from 1985 to 2000 was marked by foundational discoveries, including the identification of fullerenes, the synthesis of CNTs, and early advances in composite materials. During 2000–2010, research expanded toward practical applications, such as CNT-based electronics, atomic force microscopy (AFM) tips, and the isolation of graphene. From 2010 to the present, the focus has shifted to precision synthesis—such as chirality-controlled CNTs—and advanced multifunctional composites, including graphene-CNT hybrids [74]. A notable breakthrough occurred in 2012, when IBM developed a 9-nanometer carbon nanotube transistor, demonstrating superior performance over silicon-based devices [70].

Table 7. Timeline of developments in CNTs, graphene and composite materials

Year	Development node	Material category
1985	Discovery of fullerenes (C_{60}) [75]	Fullerenes
1991	Discovery of multi-walled carbon nanotubes (MWCNTS)[76]	CNTs
1992	Gram-scale synthesis approach of MWCNTs [77]	CNT Synthesis
1993	Synthesis of single-walled carbon nanotubes (SWCNTS) [78]	CNTs
1994	First CNT/polymer composite demonstrated[79]	CNT Composites
1995	CNT AFM tips developed [80]	CNT Applications
1998	First CNT-based field-effect transistor (FET)[81]	CNT Electronics
2003	Synthesis of CNTs from renewable carbon sources [82, 83]	CNT Synthesis
2004	Isolation of graphene via mechanical exfoliation [84]	Graphene
2008	Ultrahigh-strength graphene composites reported[85]	Graphene composites
2010	Nobel Prize in Physics for graphene research [86]	Graphene
2012	Mass production of GO by chemical methods [87]	Graphene Synthesis
2015	CNTs for electrochemical CO_2 reduction [88]	CNT Applications
2017	97% chiral purity in SWCNT synthesis [89]	CNT Synthesis
2018	In vivo CNT biomedical applications (e.g., drug delivery) 28]	CNT Biomedicine
2020	Scalable graphene-CNT hybrid composites [90]	Hybrid Composites
2024	CNT sheets for lunar dust shielding [91]	CNT sheet

The synthesis of graphene fibers has evolved significantly, with various methods developed to produce high-quality, cost-effective fibers. Key techniques include wet spinning, hydrothermal strategies, chemical vapor deposition (CVD), spontaneous reduction and assembly of GO, and derivation from CNTs [92]. When graphene synthesis methods were evaluated for industrial supercapacitor use, liquid-phase exfoliation was identified as the most suitable scalable production method, balancing advantages and limitations to meet industry demands for solar energy systems [93]. Hybrid CNT-graphene materials are fabricated using methods such as solution casting, CVD, and vacuum filtration to create thin films, 3D structures, and polymer composites with enhanced electrical, mechanical, and thermal properties for energy storage, solar cells, and flexible electronics[94]. Wet spinning and CVD methods optimize parameters such as graphene size, dope concentration, spinning rate, and temperature to achieve tunable properties, including high tensile strength (up to 3,400 MPa), electrical conductivity (up to 1.19 × 106 S/m), and flexibility. Wet spinning of GO liquid crystals is a prominent method, often combined with chemical reduction (e.g., using hydroiodic acid) to enhance fiber properties. Graphene's stability is influenced by temperature and humidity: it degrades under high heat and humidity but remains stable at room temperature or in a vacuum. However, moisture affects conductivity and adhesion [95]. Wet-spun freestanding graphene fibers exhibit low thermal conductivity (1.14–1.18 W/m·K) due to phonon scattering at grain boundaries. This finding challenges assumptions and aids thermal design for graphene fiber applications [96]. Cheng pioneered a one-step hydrothermal method to produce pristine graphene fibers (GFs), confining aqueous GO suspensions to create continuous, neat fibers in a single efficient processing stage without post-treatment [97]. A dimension-confined hydrothermal method was applied to fabricate high-strength graphene fibers in one step. Using an 8 mg/ml GO suspension in 0.4 mm glass capillaries heated at 230°C for 2 hours, this process fabricates meter-long fibers with diameters of 5–200 μm and a strength of 180 MPa. The confined geometry promotes dense π-π stacking of graphene sheets during hydrothermal reduction, enabling precise control over fiber dimensions while achieving remarkable mechanical properties. This scalable process yields continuous fibers from minimal GO solution (1 ml produces more than 6 m of fiber), offering new possibilities for graphene-based textiles and composites [98, 99].

Wet spinning aligns well with roll-to-roll textile production, while hydrothermal methods require adaptation for continuous processing. Both face scalability challenges for graphene fibers, but wet spinning offers nearer-term industry compatibility with existing infrastructure. Table 8 provides a refined and well-structured comparison for electronic fiber fabrication and applications. Aligned carbon nanotube fibers serve as effective working electrodes in fiber-shaped energy harvesting devices, providing both rapid charge transport and a high surface area for dye adsorption. Their robust mechanical structure also facilitates efficient charge transport and the integration of active materials [100]. Innovative approaches leveraging carbon nanotube films, nanofiber electrodes, and novel architectures are driving advancements in these systems. Carbon nanotube films improve charge transport and capacity, nanofiber electrodes enhance catalyst dispersion and electrocatalytic activity; and optimized architectures minimize interfacial resistance to facilitate efficient electron and ion transport [101, 102]. Composite carbon nanofiber aerogels can exhibit a three-dimensional porous structure with an internally continuous conductive network, demonstrating the capability to monitor a wide range of relative humidity (10% to 95% RH) [103]. Graphene's exceptional properties enable smart textiles with enhanced electrical, thermal, and mechanical performance[104]; fabrication methods include electrochemical deposition for direct conductive layer formation [105] and in situ polymerization to enhance graphene-polymer adhesion[106].

Table 8. Comparative of electronic fiber materials and fabrication methods

Category	Materials/ Methods	Conductivity (S/m)	Strength (MP)	Stretchability (%)	Key Advantages	Limitations	Primary Applications
Metals	Ag NWs/Ag NPs (Chemical) [107]	2.45×10^6	2.8	900	High conductivity, flexibility	Poor adhesion, oxidation risk	Strain sensors
	EGaln/CBs (Thermal drawing)[108]	1×10^6	4.2	500	Liquid metal flexibility	Complex fabrication	Optical fibers, sensors
	Cu NWs (Dip coating) [109]	5×10^5	-	100	Low-cost, scalable	Limited stretchability	Electrical heaters
Polymers	PEDOT:PSS (Wet spinning)[110]	1.67×10^4	100	20	Lightweight, biocompatible	Low conductivity	Supercapacitors
	Conductive hydrogel [111]	2×10^4	5.6	1180	Extreme stretchability	Water evaporation issues	Wearable sensors
Carbon	SWCNT fibers (Twisting) [112]	4.4×10^6	110	285	High strength, thermal stability	Costly production	Structural electronics
	Graphene (CVD)[113]	2.5×10^7	40	7.1	Ultra-high conductivity	Brittle, limited scalability	Precision sensors
	rGO fibers (Twisting)[114]	6×10^6	23	40	Balanced properties	Moderate performance	Thermal sensors

3.1.1 Graphene oxide reduction mechanisms

Table 9 shows that GO reduction mechanisms vary by reagent, each with unique advantages and limitations. Hydrothermal methods and CVD enable precise control over fiber dimensions and structural integrity, while spontaneous reduction and CNT-derived techniques offer scalable production of high-performance GFs. These advancements have enabled the fabrication of GFs with applications in energy storage, sensors, and wearable electronics, demonstrating superior mechanical, electrical, and thermal properties compared to traditional carbon fibers. Graphene fibers, fabricated through methods such as wet spinning, hydrothermal synthesis, microfluidic design, and plasticization spinning, exhibit a wide range of tensile strengths (192 to 3,400 MPa) and electrical conductivities (0.1×10^4 to 1.19×10^4 S/m). Higher reduction temperatures (up to 3000 °C) and advanced techniques like defect control and plasticization spinning significantly enhance both mechanical and electrical properties. Synergistic toughening and microfluidic design also contribute to superior performance, demonstrating the impact of fabrication and reduction methods on GF properties [49]. The incorporation of carbon nanomaterials into PV technologies offers significant advantages over those in the commercial solar cell market. The advancements in PV technologies aim to move carbon-based solar cells from the laboratory scale to industrial applications for end-user technologies. The practical applications of carbon-based solar cells with advanced performance metrics appear promising for future-generation energy harvesting. Obstacles facing PVCs can be effectively addressed through further research into emerging material designs, innovative processes, and novel device configurations [44, 115]. For instance, a graphene-based solar absorber with concentric square/circular ring resonators on $LaAlO_3$ /Ti achieves 95.43% broadband absorption (200-3000 nm). Its machine learning-optimized design shows 94.91% (visible) and 98.02% (IR) efficiency, with angle/polarization resilience, enabling cost-effective solar thermal applications [116].

Table 9. Reduction methods of GO into reduced GO

Method	Mechanism	Advantages	Disadvantages
Hydroiodic acid (HI)	Iodination of alcohols, ether cleavage, aromatic iodide reduction [117, 118]	Works at room temperature on various GO forms	Strong acid, requires careful handling
Ascorbic acid	Reduces epoxide/di-hydroxyl groups. stabilized by π-π interactions[119, 120]	Non-toxic, environmentally friendly	Slower reaction kinetics
Hydrazine monohydrate	Nucleophilic attack on epoxide groups, forms C=C bonds via diimide elimination[121]	Effective aqueous reduction, industrial applicability	Highly toxic and hazardous
Thermal annealing	Oxygen groups decompose (CO/CO_2), gas pressure exfoliates layers[122]	No chemical residues, scalable process	High energy, unsuitable for polymers

3.1.2 Carbon nanofiber

Aligned carbon nanotube fibers have emerged as promising electrodes for fiber-shaped energy harvesting and storage devices due to their exceptional structural flexibility, stability, desirable mechanical and electrical properties, and high porosity and surface area. These high-performance carbon nanotube-based fiber devices can be seamlessly integrated into textiles using conventional weaving processes, making them ideal for wearable electronics [123-125]. Aligned carbon nanotube fibers, with their superior electrical and mechanical properties, are produced by spinning from carbon nanotube solutions, carbon nanotube aerogels, or aligned carbon nanotube arrays, or by twisting carbon nanotube films [100]. The electrostatic spinning method is also used also to fabricate carbon nanofiber and molybdenum disulfide composite materials. Comparing different electrode types, researchers found that the pretreated macroporous silica nanofiber composite counter electrode, prepared by the electrospun method, exhibited higher efficiency. Fiber-shaped organic solar cells incorporating carbon nanotube fibers can be used them as anodes [47]. CNTs are used for photo-conversion and counter electrode construction in liquid electrolytes, utilizing redox reactions. Traditional silicon solar cells efficiently convert some infrared light but lose much of the visible spectrum energy as heat, while longer wavelengths remain unused. Researchers are developing nanomaterial-based thermal emitters to capture wasted energy, potentially boosting solar cell efficiency to a theoretical 80%, far surpassing the current mid-30% efficiency of silicon-based panels; this approach leverages thermophotovoltaic (TPV) principles to enhance energy conversion from sunlight[71].

3.2 Property optimization

Recent advancements have focused on using carbon nanomaterials as electrodes, transport layers, active layers, or intermediate (interfacial) layers to improve the efficiency and stability of solar cells [126]. As shown in Figure 3, graphene is a two-dimensional material with a thickness of just one atom. While both graphene and graphite are forms of carbon, they have distinct structures and properties. Graphite consists of multiple layers of carbon atoms arranged in hexagonal rings, held together by weak van der Waals forces [127]. Carbon/graphene quantum dots (CQDs/GQDs) derived from plastic waste offer excellent photoluminescence, stability, and versatility for use in sensors, bio-imaging, catalysis, and energy applications. This approach could promote waste management and a circular economy while enabling high-value applications [128]. GQDs, which are sub-20 nm graphene fragments, exhibit exceptional optoelectronic and catalytic properties. Green synthesis and modification strategies enhance their utility in sensors, energy storage, and environmental applications like CO_2 conversion. Sustainable scale-up remains a key challenge [129]. Natural graphite is used in thermal management, battery electrodes, and the nuclear industry. Graphene, on the other hand, is utilized in various applications across electronics, medicine, and other fields due to its unique properties (see Figure 4).

In contrast, graphite is commonly used in pencils, lubricants, batteries, and as a reinforcing material [130-132]. Graphene and CNTs exhibit exceptional mechanical properties, with tensile moduli reaching ~1 TPa for graphene and 0.9-1.7 TPa for CNTs. Numerical modeling reveals that CNT-graphene composite foams (CGFC) significantly outperform pure graphene foams (GF), demonstrating 3.7× higher tensile strength (66.5 vs 18.0 MPa) and 3.1× greater toughness (34.4 vs 11.2 MJ/m³). This enhancement stems from improved inter-flake connectivity via CNT bridges (GCG contacts). (1) reduced graphene thickness which increases contact points, and (2) greater CNT number/length which enhances long-range connectivit. These findings provide critical design guidelines for advanced nanocarbon materials [133, 134]. Graphene's coefficient of thermal expansion (CTE) is typically negative but can shift with temperature.

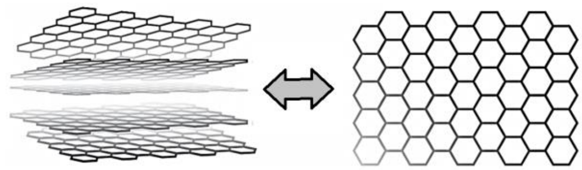

Figure 3. Structural difference between graphite and graphene [7]

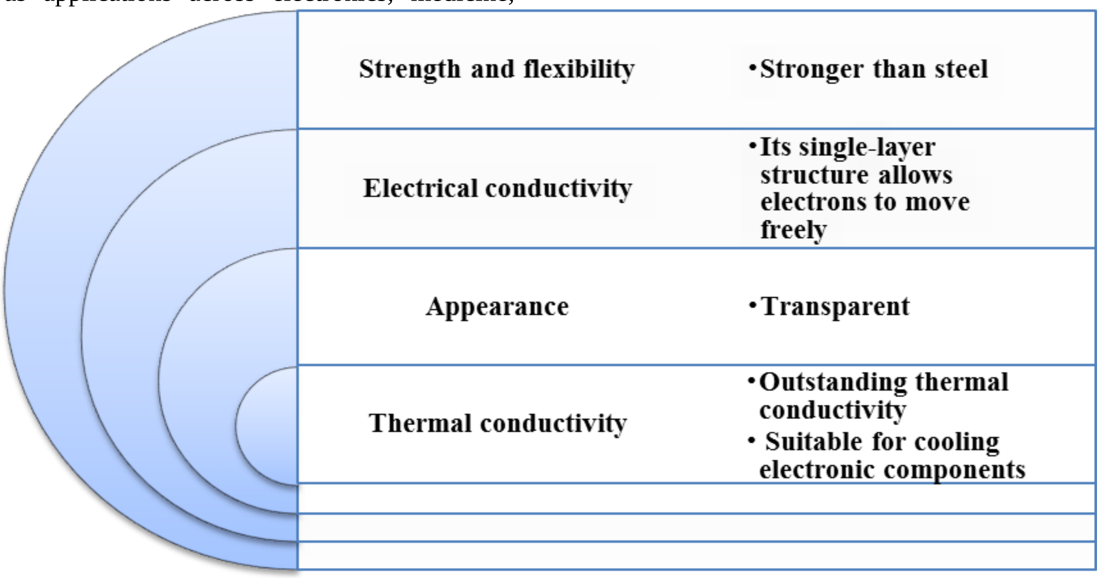

Figure 4. Main graphene properties[135, 136]

While remaining negative up to 127 ºC, substrate-induced strain critically impacts its properties. Above ~77 ºC, the CTE may turn positive. Temperature-dependent Raman spectroscopy reveals these trends, emphasizing the need to account for thermal mismatch effects in experiments, especially at cryogenic or high temperatures, to accurately interpret graphene's behavior [137]. A solar cell with a 5–10 μm diameter core electrode has been developed, incorporating carbon fiber and active components in a core-shell PV structure [138]. A core/shell graphene/Si quantum dot structure was designed to create an intermediate band in silicon solar cells; a super lattice of these dots forms a 0.3 eV mini-band, boosting the carrier generation rate and increasing the short-circuit current density from 211.5 A/m² to 364.2 A/m² [139]. The fiber-shaped dye-sensitized solar cells (FDSSCs) were enhanced using $ZnCo_2O_4$/carbon fiber counter electrodes, achieving 8.3% efficiency (an 8% improvement over platinum). The cells excel in low-light conditions (9% efficiency), offering sustainable, cost-effective solutions for wearable and textile-integrated solar applications [140]. Incorporating GO or graphene into Copper Indium Gallium Selenide (CIGS) solar cells enhances efficiency, particularly when GO is used as a back surface field (BSF) to improve charge collection. This integration boosts power conversion efficiency by optimizing parameters such as thickness and acceptor concentration, while also addressing shunt and series resistance, as well as temperature effects. A peak efficiency of 33.28% has been achieved, and studies on temperature effects provide deeper insights into performance, indicating significant promise for future solar cell technology. A copper indium gallium selenide solar cell with a reduced GO back surface field layer (BSFL) is predicted to achieve a conversion efficiency of 24%. Graphene also shows potential as a window layer material in copper indium gallium selenide solar cells due to its excellent optical and electrical properties [141]. Its derivatives have been applied to various types of PSCs, including use as hole transport materials (HTMs) due to their excellent charge transport properties. Among these, GO was the first to be used as an HTM in inverted iodide/chloride mixed halide perovskite-based planar-structured PSCs [45]. Graphene, with its extremely high surface area and low electrical resistance, is also used to grow CNTs for electrode applications. In hybrid cars, CNTs are used in ultracapacitors to collect electrical charge. Carbon nanofibers and graphene are widely used as electrode materials to enable high-speed recharging in lithium-ion battery electrodes [48]. Composite materials, which combine two or more materials with different chemical and physical properties, produce a material with distinct characteristics. Compared to traditional materials, composites can enhance the properties of base materials and are applicable in many situations. They offer advantages such as design flexibility, specialized chemical and physical properties, and resistance to a wide range of chemicals. These properties make composites beneficial for addressing critical issues related to the efficiency and operational stability of PSCs [142]. Adding 5wt% of LSM nanoparticles synthesized by sonochemistry to a PSC boosted its efficiency by 49% (from 8.33% to 12.41%) and significantly improved its current density and film morphology [143].

4. Graphene and perovskite solar cell

Silicon solar cells dominate the market with 20% efficiency, maintaining industry leadership for two decades due to their proven performance and reliability [144].Carbon-based SCs with silicon, perovskite, quantum dots and hybrid materials highlight the progress and future challenges for next-generation PVs [44]. Key areas of research focus include optimizing graphene fiber doping, improving interfacial contacts, and scaling up production. Scientists have found that adding a small amount of fluoride to perovskite forms a protective coating, enhancing solar cell stability. Metal halide perovskites (MH-PSCs) deliver efficient, affordable solar solutions despite rigidity challenges. Four advanced architectures—IBC, LC, FS, and SC PSCs—enable flexible, lightweight integration for wearables, building-integrated PV, and electric mobility while overcoming efficiency limitations [145]. Table 10 shows key aspects of PSCs. Researchers have also increased the efficiency of materials that form the basis for future PVCs. Similar to silicon-based solar cells; PSCs are composed of a mix of inorganic and organic molecules that capture light and convert it into electricity. Perovskite PV devices are simpler, cheaper, and more flexible than silicon-based cells. Investigators have developed a new type of solar cell that combines two distinct layers of sunlight-absorbing materials [48]. Graphene enhances PSCs performance when used as an intermediate layer. It stabilizes the perovskite structure, extending its lifetime by approximately 91%, and improves electron flow, resulting in a 23% reduction in electron mass and a 26% increase in photoconductivity. These findings support the use of graphene to improve hybrid PSCs [146]. Graphene boosts PSC efficiency with its high carrier mobility. Using plasma-enhanced chemical vapor deposition (PECVD)-grown graphene a hole transport layer in ITO/PCBM/CsPbI3 structures, SCAPS-1D simulations reveal efficiency is linked to plasma parameters. Optimal electron/ion densities and temperatures enhance performance via Debye length modulation [60]. With aligned nanofibrous metal oxide electrodes, excitonic solar cells achieve high efficiency [147]. Graphene fibers enhance solar cell performance by broadening the absorbed spectrum and providing high tensile strength, making them suitable for use on various substrates. Graphene can function as an electrode, active layer, or electron acceptor. However, research on graphene-based solar cells remains primarily confined to laboratory settings [51]. Various functional components can be integrated with graphene fibers through post-treatment and in-situ hybridization methods. The resulting graphene-based composite fibers demonstrate broad applicability, particularly in energy conversion and storage devices. These applications include supercapacitors, lithium-ion batteries, solar cells, self-powered devices, and thermoelectric generators [49].

Table10. Key aspects of PSCs [148, 149]

Category	Description	Impact on Performance	Challenges
Power conversion efficiency (pce)	Increased from 3.8% to **25.2%**, surpassing CIGS and CdTe solar cells.	High PCE makes PSCs competitive with silicon solar cells.	Stability and scalability issues hinder commercialization.
Material properties	High ion mobility, long charge carrier lifetime, low exciton binding energy, and excellent charge transport.	Enhances light absorption and charge separation.	Sensitivity to environmental factors (moisture, heat).
Crystal structure tuning	Adjusting A, B, or X sites in ABX_3 perovskite structure.	Modulates bandgap, light absorption, and stability.	Requires precise compositional engineering.
Device architecture	Layer composition (ETL, perovskite, HTL) and structure influence performance.	Affects open-circuit voltage (V_{oc}), fill factor (FF), and short-circuit current (J_{sc}).	Optimization needed for charge extraction.
Synthesis methods	Solution processing, vapor deposition, and crystal growth engineering.	Determines film quality and defect density.	Reproducibility and large-scale fabrication challenges.
Charge transport layers	Electron (ETL) and hole transport layers (HTL) guide carriers to electrodes.	Reduces recombination losses.	Material compatibility and degradation under operation.
Physical mechanisms	Charge transport, ion migration, defects, and ferroelectric effects.	Understanding improves device design.	Complex interplay of factors affects stability.
Stability and toxicity	Degradation under moisture, heat, and light exposure. lead-based toxicity.	Critical for long-term performance and commercialization.	Needs encapsulation and lead-free alternatives.

Researchers have also created SWCNTs with four isolated sub-nanometer halide perovskite structures [150]. In organic PV device applications, the preferred diameter for CNTs is below 20 nm, with typical diameters ranging from 2 to 10 nm for SWCNTs and 5 to 100 nm for MWCNTs [151, 152]. CNTs feature a cylindrical nanostructure with an exceptional length-to-diameter ratio that can surpass 130 million. In DSSCs, bio-carbon electrolytes showed superior stability during 3000-hour light-soaking tests, degrading more slowly than traditional platinum catalysts, highlighting their potential for durable solar energy applications [46]. Graphene fibers improve solar cells by enhancing transparent electrodes with high flexibility, reducing charge transport resistance, reinforcing mechanical stability, stabilizing perovskite layers against ion migration and thermal stress, and providing cost-effective, conductive back contacts. These advances boost efficiency and reduce costs across multiple solar cell components. PSCs achieve 25.2% efficiency, rivaling silicon cells. Their superior charge mobility, tunable bandgap, and solution processability enable high-performance PVs [153-155]. However, stability and toxicity challenges must be addressed for commercialization. Optimizing device architecture, transport layers, and defect passivation can further enhance PSC performance for future renewable energy applications [148, 156]. A high-accuracy machine learning model has been developed to predict the key electronic bandgap and energy levels of halide perovskites; it accelerates the rational design of these materials for tailored optoelectronic properties and next-generation solar cells [157].

5. The flexible fiber-shaped solar cells

The flexible fiber-shaped solar cells have achieved efficiencies exceeding 9% under air mass 1.5 global irradiation conditions [59]. Carbon nanomaterials show high potential as functional layers for high-efficiency and stable solar cells [44]. Researchers have studied solar cells based on thick sheets of graphene and molybdenum diselenide [48]. Nanoporous germanium flexible layers have been developed to produce lightweight solar cells for electronic applications. Low-cost solar cells have been fabricated using titanium dioxide nanotubes filled with polymers [94]. Recent advances in carbon nanomaterials for flexible solar cells focus on material synthesis and structural design, including light confinement techniques to boost electron generation. Current challenges and future directions are outlined to guide further development of these promising materials [47]. Organometal halide perovskites are significant PV materials with substantial potential for next-generation commercial PV modules. For future commercial applications, the efficiency and stability of PSCs must be improved. Carbon nanomaterials are promising candidates for addressing these issues due to their unique properties, low cost, and abundance [45]. PSCs use transparent ITO (Indium Tin Oxide) or FTO (Fluorine-doped tin oxide) electrodes atop glass, enabling light transmission. Below lies the electron transport layer (ETL), which conducts electrons while blocking holes from the active layer [158].

6. Solar textiles

The textile industry has seen significant improvements through the application of new materials [159-165] and technologies [166-168]. Developing flexible PV textiles involves weaving and knitting processes that subject materials to significant stress from friction and bending. This demands robust inter-layer adhesion and exceptional flexibility to ensure durability. These textiles must endure bending, stretching, weathering, and laundering to remain functional over time. By integrating lightweight fiber-shaped solar cells, these textiles can power wearable electronics while maintaining environmental sustainability. A refined and well-structured summary of the history of solar textiles is provided in Table 11. Textile hybrid electronics (THE) merge flexible and rigid components, balancing performance and comfort [169].

Table 11. Evolution of solar textiles – key milestones [56, 167, 170]

Decade/ Year	Development	Significance
1970s	Early flexible solar cells using a-Si	Enabled solar integration on non-rigid substrates for the first time.
1980s	Organic Photovoltaics (OPVs) and conductive polymers discovered	Laid foundation for lightweight, printable solar cells (Nobel Prize-winning work).
1990s	Thin-film solar cells (CdTe, CIGS) developed. NASA explores space applications	Improved flexibility for satellites/spacesuits. military interest began.
2000s	Konarka commercializes OPVs. US military invests in solar textiles	First attempts at mass production. focus on reducing battery weight for soldiers.
2010–2016	• Woven solar fabrics (Univ. of Southampton, 2010) • Wire-shaped solar cells (Georgia Tech/Xiamen Univ., 2013) • Energy-harvesting fabrics (solar + triboelectric, 2016)	Shift toward seamless textile integration. hybrid energy solutions emerged.
2017–2019	• Ultrathin PVs wrapping human hairs (2017) • Solar-embedded yarn (2019)	Achieved invisibility and wearability in solar textiles.
2021	Hybrid cotton fabric (sunlight + motion energy) – Khalifa Univ.	Multi-source energy harvesting for practical daily use.
Present	Commercialization of solar jackets, PV-building fabrics	Focus on efficiency, durability, and scalability for consumer/industrial markets.

Wearable e-fibers and textiles merge comfort with functionality, enabling health monitoring, energy harvesting, and human-machine interfaces [171]. Efforts to develop next-generation flexible electronics have led to the creation of deformable, breathable OPV textiles using fiber-shaped polymer solar cells with twisted cathode and anode fibers. This integrated approach combines device fabrication, weaving, and circuit connections, enhancing performance and enabling commercialization [50]. Each method presents critical trade-offs: spinning balances performance against scalability challenges, weaving exchanges flexibility for stability, and encapsulation prioritizes protection over comfort. These inherent constraints must be addressed for optimal wearable device performance. Spinning creates elastic strain sensors (300% stretchable) and high-density supercapacitors. Weaving produces stable, waterproof e-textiles for sensing and energy harvesting. Encapsulation enables sensitive (GF>3500), stretchable sensors using eco-friendly materials. Each method tailors GFs for specific wearable applications, as summarized in Table 12. Furthermore, the table shows that weaving enables stable e-textiles (sensors, energy harvesters), spinning produces high-performance fibers (supercapacitors, strain sensors), and encapsulation enhances durability but reduces breathability. Each method balances performance and wearability. Spinning techniques face issues such as environmental sensitivity and complex coagulation requirements. Woven structures lack stretchability and show durability issues in OLED/TENG textiles. Encapsulation reduces breathability and increases bulk, while eco-friendly versions sacrifice power density. Breathable textile electronics require fiber-shaped TEs instead of solid films, ensuring air permeability while maintaining conductivity. Flexible substrates and protective coatings can enhance durability without compromising comfort or mechanical performance in wearable applications [172, 173]. Table 13 presents the proposed classification system for graphene-textile integration.

Table 12. Functional GFs in wearable electronics

Fabrication technique	Device type	Key features	Advantages
Spinning [174-177]	Strain sensors (e.g., core-spun yarns)	Metal-coated elastic cores (PU/Ni/Cu)	Ultra-elastic (0–300% strain), lightweight (1.5 mg cm^{-1})
	Super capacitors, torsional motors	Wet-spun GO/CNT fibers, helical structures	High energy density (187.6 mF cm^{-2}), humidity-responsive
Weaving [178-181]	Strain sensors, Energy harvesters (e.g., magneto electrical fabrics)	Plain-woven structures, interlaced conductive yarns	High stability, scalable, industrial compatibility
	OLED textiles, TENGs	Matrix-addressable networks, triboelectric layers	Flexibility, waterproof operation
Encapsulation [182-185]	Sustainable sensors (graphene/NR elastomers)	Printable, biodegradable materials	Eco-friendly, conformable (270 μm thickness)
	Strain/pressure sensors (Ecoflex/rGO)	Polymer encapsulation (Ecoflex, PDMS)	High sensitivity (GF > 3500), stretchable (300% strain)

Table 13. Three-tiered framework: integration level, functionality, and scalability [174-185]

Tier	Classification Criteria	Subcategories
1. Integration Level	How graphene is incorporated into textiles	a. Fiber-Level (spun/wet-spun GF yarns) b. Coating-Level (graphene inks/pastes) c. Composite-Level (graphene-polymer blends)
2. Functionality	Primary application-driven performance	a. Sensing (strain/pressure/temperature) b. Energy (TENGs/supercapacitors) c. Actuation (shape-memory/robotics)
3. Scalability	Manufacturing readiness and sustainability	a. Lab-Scale (proof-of-concept) b. Industrial-Scale (roll-to-roll/weaving) c. Circular (biodegradable/recyclable)

Solar textiles' success hinges on solving key mechanical challenges: developing flexible, stable material combinations compatible with textile structures while maintaining efficient carrier transport and reliable electrode integration. Failure in these areas could limit practical adoption [186]. E-textiles incorporating graphene and GO are widely studied due to their excellent conductivity, mechanical robustness, and biocompatibility [187-189]. The oxygen functional groups in GO enhance adhesion to fibers via van der Waals forces, significantly improving wash fastness and resistance to mechanical stress [189, 190]. Graphene fibers uniquely integrate textiles and electronics, forming high-performance materials that combine mechanical durability with inherent flexibility for advanced wearable technologies [191]. Graphene-enhanced PSCs achieve 18.2% efficiency through improved charge collection. Their stability also improves under light and heat, enabling scalable production for commercialization [192]. Flexible PSCs promise lightweight, efficient power for wearables. Critical hole transport layers enable hole extraction, requiring high mobility, stability, and proper energy level alignment. Advances are addressing durability, fabrication, and integration challenges for portable energy [193]. Poly(triarylamine) excels in thermal stability for PSCs, but its toxic processing necessitates greener alternatives to enable sustainable large-scale production [194]. Flexible PSCs require substrates like PEN, PET, or metal foils, which must balance stability, conductivity, and thermal resistance. Flexible willow glass enables high-temperature processing, overcoming the limitations of opacity and brittleness in traditional options [195]. Water-dispersible NiOx nanocrystals enable annealing-free fabrication of flexible PSCs, enhancing hole extraction and stability to achieve 14.53% power conversion efficiency [196, 197]. Metal nanofibers pose biocompatibility risks and lack sufficient conductivity for wearable electronics, limiting their practical use despite functionalization attempts [198, 199]. Graphene-coated e-textiles show around 10–20% resistance increase during bending. they show improved wash stability (40 cycles) and bending durability with adhesive or protective layers [172]. Heat-pressed SIS films achieve robust textile adhesion (greater than 1000 J/m²), with polyester reaching 11,000 J/m². Non-coated textiles enable deeper elastomer infiltration, enhancing mechanical interlocking compared to coated fabrics. Peel testing quantifies bond strength (e.g., $G_c=2F_c/w$) [200]. Recent advancements, such as those in PSCs, further improve their stability and efficiency, making them highly practical for use in smart textiles. Table 14 presents graphene-based textile composites for solar heating applications in the form of graphene hybrid systems. Graphene fibers enable advanced wearable electronics with superior conductivity, strength, and flexibility. Graphene-functionalized composites offer promising solutions, enhancing warmth and reducing heat loss by functioning as wearable joule heaters for personalized thermal management and therapy [8].

Table 14. Graphene-based textile composites for solar heating applications (graphene hybrid systems)

Material composition	Material	Fabrication method	Solar absorption efficiency	Key solar-thermal properties
rGO/MXene ($Ti_3C_2T_x$)[201]	Cotton	Dip-coating + spray	more than 95%	Synergistic plasmonic effect, enhanced IR retention
rGO/Ag NPs [202]	Cotton	In-situ reduction	~93%	Localized surface plasmon resonance (LSPR)
Graphene/PPy [203]	Cotton	Polymerization	89%	Conductive polymer enhances charge transfer
Tourmaline /graphene /WPU [204]	Cotton	Spray coating	91%	Far-IR emission (4–14 µm) for body warming
rGO/CNT [205]	Nonwoven fabric	Vacuum filtration	~90%	Broadband absorption, structural stability

Solar textiles promise transformative potential for the textiles and solar energy sectors, contingent on breakthroughs in: (1) flexible, stable materials, (2) efficient carrier transport, (3) precise electrode integration, and (4) scalable manufacturing. Success ensures widespread adoption; failure risks relegation to academic study [186]. Fabrication techniques like wet spinning and electrospinning produce high-performance fibers for sensors, energy storage, and smart textiles [206]. Scientists are integrating flexible solar cells into smart textiles and wearable devices, making them ideal alternatives to traditional solar technologies [207, 208]. However, the efficiency of CNT-based organic solar cells (OSCs) lags behind traditional OSCs due to limitations such as the low optical transparency of CNT-based electrodes and charge transport layers in the visible spectrum. This restricts photon absorption in the active layer, reducing exciton generation and photocurrent production. Consequently, these drawbacks hinder the overall performance of CNT-based OSCs compared to conventional materials [52]. Flexible fiber-shaped solar cells can now be woven into textiles, serving as a crucial energy source for wearable electronic devices [54, 55]. These solar cells can be effectively shielded from water, washing agents, and mechanical stress, enabling them to withstand repeated domestic laundry cycles. This breakthrough greatly improves the practicality of incorporating solar technology into everyday textiles. PV textiles, demonstrating high potential, have been utilized to create flexible and self-powered devices [56], thereby promoting sustainability in wearable technology [167]. Electrospun nanofibers and nonwoven fabrics for textile PV devices are a key factor in their effectiveness for powering wearable devices, converting sunlight into electrical energy for various applications [57]. Novel PSC textiles, created by depositing a continuous layer of perovskites onto aligned titanium dioxide nanotubes, significantly enhance stability. These innovative textiles show consistent power conversion efficiency even under extreme temperatures, maintaining performance at -20 °C and 100 °C for 240 hours. Moreover, they retain approximately 90% of their efficiency across a wide temperature range from -40 °C to 160 °C. This technological advancement significantly enhances the environmental adaptability of fiber-based solar cells, making them highly suitable for wearable and portable electronics applications [58].

Recent advancements in smart textiles highlight the synergistic integration of single-walled carbon nanotubes (SWCNTs) and polyaniline (PANI), enhancing mechanical, thermal, and electrical properties for wearable electronics [209]. A key factor in their effectiveness for powering wearable devices [56] is their ability to convert sunlight into electrical energy for various applications [210, 211]. Rugged, deformable soft devices are key for wearable tech. Textile-based electronics face challenges in in creating robust, flexible interconnections. Researchers present multilayer liquid metal (LM) circuits with strong adhesion (11,000 J m^{-2}), stretchability (300% strain), and water resistance, paving the way for durable textile electronics [212]. Heat-pressing styrene–isoprene–styrene elastomer films onto textiles achieve strong adhesion, with fracture energies exceeding 11,000 J m^{-2} for high-denier polyester. Non-coated, loose-weave textiles (e.g., cotton, polyester-spandex) allow deeper elastomer infiltration, enhancing adhesion. Solvent welding further bonds additional SIS layers without compromising strength, enabling multilayer soft circuits. A 5 kg weight test confirms robust adhesion, supporting rugged applications like underwater wearables [213]. Stretchable e-textiles were developed by laminating conductive patterns onto knitted fabric, testing their durability under stretching and washing. A knee sleeve with printed carbon rubber electrodes is designed for wearable electrotherapy, demonstrating practical medical applications [214]. Figure 5 shows the major applications of graphene fibers in modern solar cells. By leveraging their unique properties, further innovations can be achieved, paving the way for next-generation solar cells with enhanced performance and novel functionalities [215]. Solar textiles require breakthroughs in flexible materials, carrier transport, electrode integration, and scalable manufacturing. Success enables widespread adoption; failure limits them to academic research.

From the above, graphene PV systems can be embedded into textiles via:

1) Coating/Printing: Cost-effective for nonwovens, but less durable.
2) Fiber Spinning: Seamless for knits, offering a balance between flexibility and conductivity.
3) Lamination: Robust for weather-resistant fabrics, yet stiff.
4) Hybrid Weaving: High-performance but costly.

The best method depends on the fabric type (woven/knit/nonwoven) and application needs (durability, flexibility, breathability).

7. Challenges and prospects

Some researcher synthesizes advancements and challenges in solar PV technology, highlighting the gap between lab efficiency and real-world performance. It identifies critical barriers in storage, recycling, and grid integration that must be overcome through coordinated policy and research to meet global sustainability goals [216]. CNTs/conducting polymer-based hybrid solar cells are still in their early stages compared to other solar cell types, primarily due to the inherent challenges associated with conducting polymers. However, CNTs when used as transparent electrodes offer low resistivity, excellent conductivity, and flexibility [217, 218]. The primary challenges include resource availability (e.g., silicon, silver, and rare earth elements) and the energy transition, which requires upgrading grid infrastructure and energy storage systems [219]. Research on waste-derived carbon nanomaterials (from biomass/plastics) for enhancing solar cell efficiency and sustainability covers synthesis methods, component integration, performance benefits, challenges, and future applications in renewable energy technologies [220].

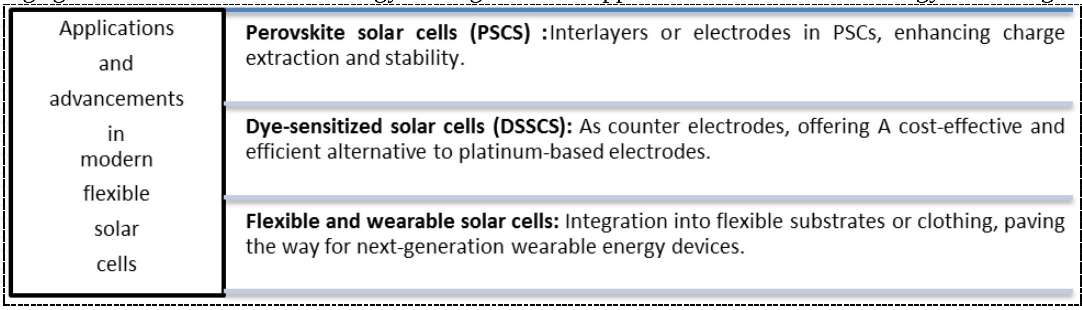

Figure 5. Applications of graphene fibers [215, 221-224].

Recent research focuses on integrating solar cells with supercapacitors for sustainable power. These self-charging systems combine high efficiency, reliability, and cost-effectiveness, though challenges remain in scalability and energy conversion optimization [225]. This section discusses challenges and future opportunities in graphene fiber research and applications, graphene fibers face key challenges and opportunities in advancing modern applications (Figure 6), achieving homogeneous GF-polymer composites without surfactants remains critical for maintaining electrical conductivity. Meanwhile, advanced graphene microfibers with tunable conductivity are emerging for wearable and environmental sensing. The global graphene market, projected to exceed \$2 billion, highlights growing demand across healthcare, energy, and defense sectors, underscoring the need for continued innovation in GF development [92, 226-228].

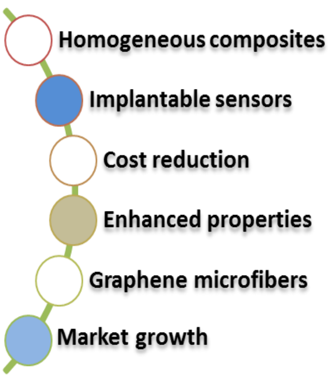

Figure 6. GFs opportunities in modern applications [88, 219-221]

GF-based solar cells achieve efficiencies of 3.25–8.45%, while integrated self-powered devices combine energy conversion (4.2%) and storage (472 mF/cm^2). Challenges include curvature losses, dependence on Pt, and component mismatches. Table 15 summarizes the key aspects of GF-based solar cells and self-powered devices. Challenges like grid stability, financing, supply chains, and political resistance could hinder progress. Effective policies addressing these barriers are crucial to accelerating the clean energy transition [229]. Solar cells address energy and environmental challenges, with PSCs offering cost-effective, efficient, and flexible solutions. Integrating graphene-based materials enhances PSCs by improving charge transport, stability, and exciton dissociation [230]. Interdisciplinary research and policy support are required to fully realize the potential of GF-based technologies for multifunctional applications.

Hybrid life cycle assessment (LCA) combines process-based and input-output (EIO-LCA) methods to systematically evaluate the environmental impacts and long-term degradation in PV systems. This approach addresses key limitations:

1. Comprehensive System Boundaries**:** it captures indirect supply-chain effects (e.g., material aging, efficiency loss) through multi-regional input-output (MRIO) matrices [231].
2. Multi-Metric Tracking: it simultaneously quantifies GHG emissions ($kgCO_2$-eq), toxicity, acidification, and resource use degradation [232].
3. Validation: Process-level data (e.g., lab-scale $1m^2$ PV) is used to verify EIO coefficients , thereby minimizing truncation errors [233].

The framework identifies degradation hotspots (e.g., encapsulant weathering, electrode corrosion) and benchmarks alternatives (e.g., graphene vs. ITO electrodes) [234-236]. Applied to wind turbines and biofuels, hybrid LCA proves effective for predicting service-life performance degradation and optimizing materials to quantify circular economy benefits [231]. Gold dominates toxicity impacts (82% aquatic / 43% human) in PV systems due to energy-intensive mining and toxic discharges[237]. Cadmium and tellurium raise concerns over scarcity and ecotoxicity, driving research into more abundant alternatives. Material substitution must address [238, 239] Marine/freshwater toxicity (gold, FTO glass), acidification / eutrophication (gold production), and human toxicity (Spiro-MeOTAD, manufacturing emissions). Below is Table 16 summarizing nanomaterial shedding in textiles, user exposure, and related concerns regarding occupational exposure, biodegradability, and toxicity.

Table 15. Comparison of GF-based solar cells and self-powered devices

Device Type	**Key Properties**	**Cost Factors**	Materials /Structure	Challenges
GF-based dye-sensitized solar cell [240]	- Flexibility (bend radius < 2mm) - Conductivity: ~10^5 S/m - Efficiency: 5.2% (vs. 8% planar)	- Graphene fiber: ~$120/m - Ti wire: $5/m	Hollow multilayer graphene fiber (twisted) + TiO_2 nanotubes/Ti wire	- Lower efficiency than planar devices due to curvature
GF-based dye-sensitized solar cell [241]	- Efficiency: 7.8% - Pt loading: 0.5 mg/cm² - Stability: >1,000h	- Pt cost: $30/g - Adds ~15% to device cost	Pt nanoparticle-decorated GF + TiO_2 nanotubes/Ti wire	- Requires Pt nanoparticles for high efficiency
Self-powered device (dye-sensitized solar cell + Supercapacitor) [242]	- Energy density: 15 Wh/kg - Power density: 2 kW/kg - Coulombic efficiency: 92%	- PANI: $50/kg - CNTs: $100/g	Hollow graphene/CNTs/PANI fiber + TiO_2/Ti wire	- Mismatch between storage and conversion parts
Integrated self-powered device [243]	- Weavability: 85% retention after 50 bends - Areal capacitance: 35 mF/cm²	- Sealing materials: $20/device - Pt at G adds ~20% cost	PANI//Pt at G fiber (PANI at G for supercapacitor Pt at G for dye-sensitized solar cell)	- Sealing issues, weavability needs improvement

Table 16. Nanomaterial shedding in textiles, user exposure, and related concerns

Aspect	Key Findings/Concerns
Nanomaterial Shedding **[244-247]**	- Nanoparticles (e.g., Ag, TiO_2, ZnO, CNTs) can release from textiles due to abrasion, washing, or wear. - Higher shedding in fabrics with weak binding matrices.
User Exposure **[248-250]**	- Dermal contact, inhalation, or ingestion of released NPs. - Ag NPs in socks may penetrate skin; CNTs pose inhalation risks.
Occupational Exposure [251-253]	- Workers in textile manufacturing face inhalation risks during NP handling, spinning, or coating. - Lack of proper PPE increases exposure.
Biodegradability **[254-257]**	- Some NPs (e.g., Ag) persist in the environment; others (e.g., cellulose-based NPs) degrade more readily. - Accumulation in soil/water affects ecosystems.
Toxicity **[258-261]**	- Ag NPs: Antimicrobial but cytotoxic at high doses. - CNTs: Potential lung inflammation, fibrosis. - TiO_2: Possible carcinogenicity if inhaled.

Tables 17 and 18 compare solar technologies and summarize e-textile challenges, respectively. Table 17 compares solar technologies: Si, GO (eco-friendly, scalable), perovskites (26% lab efficiency, but with stability challenges), and hybrid desalination (multifunctional, but at an early-stage), highlighting cost, scalability, and key barriers. Table 18 summarizes the key gaps and challenges in standardization, safety and biocompatibility, industrialization and commercialization, and functional performance of e-textiles. The selection of a core energy technology is a fundamental first step in e-textile design, but each option presents a unique set of trade-offs in performance, stability, and manufacturability.

Table 17. Comparative Analysis of Emerging Solar Technologies

Technology	Pros	Cons	Scalability	Cost ($/Watt)	Key Challenges
Silicon (Si) solar cells [262]	Mature, 25% efficiency	Thermal losses, efficiency plateau	High (existing infrastructure)	0.20–0.50	Limited efficiency gains
GO from PAN fibers [263-267]	High yield (200 mg/g), eco-friendly, versatile	Natural graphite impurities require purification	High (R2R-compatible)	Lower than natural graphite	Purity control, process optimization
PSCs [268-271]	>26% lab efficiency, low-temperature processing	Stability issues, large-area efficiency drop (~11% R2R)	Promising (R2R demonstrated)	~0.70 (if scaled)	Durability, reproducibility, film quality
Hybrid solar desalination [272].	Multi-functional (energy + water)	Early-stage, integration complexity	Low (prototype phase)	N/A (early R&D)	System integration, efficiency

Table 18. Different categories, challenges/gaps, and current status of E-textiles

Category	Key Challenges and Gaps	Current Status and Needs
Standardization [123, 273, 274]	- Lack of unified testing protocols for durability, conductivity, and washability. - No global standards for e-textile manufacturing or performance.	- Urgent need for ISO/ASTM standards for reproducibility and quality control. - Industry-wide benchmarks for interoperability.
Safety and Biocompatibility [256, 260, 261]	- Limited studies on long-term skin contact effects (irritation,) toxicity. - Risks from conductive materials (e.g., silver, CNTs) leaching during or sweat exposure.	- Requires rigorous biocompatibility testing (ISO 10993). - Development of hypoallergenic, non-toxic conductive inks/fibers.
Industrialization Pathways [275, 276]	- High production costs due to complex integration processes. - Scalability issues in embedding electronics into textiles.	- Need for automated, high-throughput manufacturing (e.g., roll-to-roll printing). - Supply chain optimization for conductive materials.
Commercialization Barriers [170, 207, 277]	- Limited consumer awareness and high costs hinder adoption. - Lack of clear market differentiation from conventional wearables.	- Business models focusing on niche applications (medical, sports). - Partnerships with fashion and tech industries.
Functional Performance [55, 278, 279]	- Trade-offs between flexibility, conductivity, and durability. - Poor washability (resistance degradation after laundering).	- Advanced encapsulation techniques (e.g., hydrophobic coatings). - Integration of self-healing materials for longevity.

The comparison of emerging solar technologies highlights those critical choices. However, the viability of any energy solution is ultimately constrained by a second layer of challenges inherent to the e-textile platform itself. Therefore, the analysis of solar technologies in Table 17 must be read in conjunction with the broader commercialization and industrialization gaps for e-textiles summarized in Table 18, as the challenges in one directly compound the challenges in the other.

8. Future perspectives

PV technology is rapidly advancing, with progress in materials and architectures like perovskite and tandem cells addressing sustainability challenges and guiding future innovation [280]. Monolithic perovskite/silicon tandem solar cells are advancing rapidly, with a practical efficiency target of 37.8% set to guide future research, focusing on improving the perovskite top cell's performance through advanced passivation strategies[281]. To optimize global deployment, researchers analyze six key environmental factors—from irradiance and heat to aerosols and extreme weather—that impact solar PV performance, underscoring the need for climate-specific strategies [282]. Researchers examine how integrating solar power, radio wave energy harvesting, and AI creates synergistic solutions that address urgent societal issues, merging environmental sustainability with commercial profitability [283]. Si solar cells lead with 25% efficiency but face thermal losses. Tandem cells outperform by harnessing shorter wavelengths for higher efficiency [262]. A scalable method was developed to produce GO nanosheets from PAN-derived carbon fibers using nitric acid exfoliation. Optimal at a 5% acid concentration, it yields high-quality monolayer GO (0.9 ± 0.2 nm) with unique shapes and a high yield (200 mg/g). Characterization confirmed uniformity, enabling eco-friendly large-scale GO production for energy storage, coatings, composites, water purification, and electronics [263]. A major limitation of natural graphite-based synthesis is its low purity, often containing only 40% graphite mixed with impurities like quartz and feldspar [264], which complicate GO extraction and require extra purification [265]. In contrast, carbon fibers from PAN, processed at high temperatures, offer a cleaner source with turbostratic graphite crystallites and defect-induced strained sp^2 bonds [266, 267]. Hybrid PSCs now reach 25.2% efficiency, enabled by scalable, low-temperature coating. However, large-area R2R devices lag at ~50% of lab performance. Key challenges include reproducibility and film quality-critical for commercialization [271]. All-weather, solar-driven desalination systems of the future combine photo-thermal evaporators with hybrid technologies for sustainable freshwater production[272]. Roll-to-roll (R2R) enabled PSC production allows continuous fabrication ("Ink-IN / Module-OUT") on flexible substrates. By overcoming scaling challenges, R2R could transform lab breakthroughs into global, sustainable perovskite solutions [268]. PSCs now rival commercial technologies in lab efficiency, yet scaling remains a hurdle. The first industrially printed perovskite modules have been demonstrated using roll-to-roll methods, achieving 11% efficiency with carbon electrodes. Optimized via high-throughput testing, this approach predicts ~0.70 watts at scale, enabling cost-competitive commercialization [269]. PSCs exceed 26% efficiency but face commercialization hurdles like stability and scalable production. Some research analyzes large-scale deposition techniques (inkjet, blade coating, slot die, etc.) for R2R/S2S manufacturing, with key parameters and future engineering pathways for viable PSC technology [270]. Energy-harvesting textiles, particularly solar cells, offer a sustainable, flexible power source for wearable electronics [284]. Future PV research must prioritize advanced materials like perovskites, innovative architectures for higher efficiency and durability, and sustainable grid integration to solidify solar energy's role in the clean energy transition [285]. Laser-induced graphene (LIG) is a versatile material for space applications. It enables health monitoring on smart spacesuits and provides stray-light absorption and thermal management for telescopes, with functionality confirmed in thermal-vacuum tests [286]. Smart textiles now integrate energy harvesters like nanogenerators to become self-powered, enabling real-time health monitoring[287]. The AI-driven energy transition, while boosting renewables, also increases power demand. Success requires balancing this technological acceleration with equity, governance, and robust multi-stakeholder alliances to ensure a sustainable future [288]. AI is revolutionizing smart textiles by guiding the design of powder-based materials for energy, sensing, and robotics, For example, machine learning accelerates material discovery and enables autonomous, wearable systems, while also addressing challenges in scalability and data [289]. A lightweight AI model for automated solar panel fault detection has been deployed on a Jetson Nano; it achieves 93.14% accuracy and 44.4 m.s inference speed, enabling efficient, real-time on-site inspection without cloud dependency[290].

9. Conclusion

PV technology is poised to remain a cornerstone of the global transition to a clean and sustainable energy future. A key innovation driving this progress is the emergence of graphene fibers, which represent a transformative advance in solar textile technology by bridging the gap between nanomaterials and functional fabrics. These fibers enable the creation of PV textiles that achieve remarkable efficiencies while offering exceptional flexibility and durability. The field has already passed significant milestones, such as developing efficient CIGS/GO hybrid cells and DSSCs capable of stable, long-term operation. The unique properties of graphene fibers—particularly their high electrical conductivity, mechanical strength, and inherent flexibility—make them ideal for next-generation energy-harvesting textiles. They perform multiple roles within a solar fabric, serving simultaneously as conductive electrodes, charge transport layers, and structural scaffolds. This multifunctional nature is crucial for developing wearable solar technologies that can withstand mechanical stress and repeated deformation without losing performance. Despite this promising trajectory, several challenges must be overcome to achieve widespread commercial adoption. Key hurdles include perfecting the interface between graphene and textile substrates, optimizing large-scale production methods, and conducting comprehensive life cycle assessments to evaluate environmental impact. A particularly critical step toward sustainability is reducing the high embedded energy currently required for graphene fiber fabrication. Looking ahead, research is focusing on several promising directions. These include developing hybrid material systems that combine graphene fibers with perovskites or organic PVs; implementing advanced fabrication techniques like roll-to-roll processing; designing novel device architectures for improved light harvesting; and integrating these systems with broader smart textile functionalities. Successfully navigating the path to commercialization will require concerted, cross-disciplinary collaboration among materials scientists, textile engineers, and manufacturing experts. As advancements in material science and production technology continue to push the boundaries of the possible, the ultimate goal remains the creation of cost-effective, high-performance solar textiles for diverse applications. With continued progress, graphene fiber-based solar textiles are set to play a pivotal role in the future of both wearable electronics and sustainable energy. Commercial companies have designed flexible textile-based solar cells for powering wearable electronics, outlining their mechanisms, fabrication, and performance to overcome limitations and promote their industrial commercialization.

Nomenclature

B, P	Dopants (Boron, Phosphorus)
C_{60}	Fullerene molecule
CTE	Coefficient of Thermal Expansion ($°C^{-1}$)
Cu/In/Ga ratio	Stoichiometry control in CIGS
E_3ME	Macro-econometric model
ETL	Electron Transport Layer
FF	Fill Factor
FTT	Future Technology Transformations model
Gc	Fracture energy (J/m^2)
GF	Graphene Fiber
GQDs	Graphene Quantum Dots
GO	Graphene Oxide
HTL	Hole Transport Layer
Jsc	Short-circuit current density (A/m^2)
k	Thermal Conductivity(W/(m·K))
LIG	Laser-Induced Graphene
MP	Tensile Strength (MPa)
MWCNTs	Multi-Walled Carbon Nanotubes
NPs	Nanoparticles
OPV	Organic Photovoltaic
PANI	Polyaniline
PCE	Power Conversion Efficiency (%)
PEDOT:PSS	Conductive polymer
PSCs	Perovskite Solar Cells
PVCs	Photovoltaic Cells
PV	Photovoltaic
QDs	Quantum Dots
rGO	Reduced Graphene Oxide
RH	Relative Humidity(%)
R_2R	Roll-to-Roll (manufacturing)
S/m	Electrical Conductivity
SWCNTs	Single-Walled Carbon Nanotubes
TENGs	Triboelectric Nanogenerators
THE	Textile Hybrid Electronics
V_{oc}	Open-circuit voltage (V (Volts))
wt%	Weight Percentage (%)
η	Efficiency (General) (%)
σ	Electrical Conductivity (S/cm or S/m)
Ω	Sheet Resistance (Ohms)

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