

Advanced Functional Materials for Biomedical and Electronic Applications: Recent Progress, Challenges, and Future Perspectives

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ABSTRACT

Functional materials, whose physical, chemical, or biological properties respond in a controlled way to external stimuli, have become central to modern biomedical engineering and electronics. Advances in nanostructured carbon, two-dimensional (2D) materials, conducting polymers, metal oxides, perovskites, metal–organic frameworks (MOFs), stimuli-responsive hydrogels, and bioactive ceramics have enabled devices that were unimaginable a few decades ago, including implantable biosensors, targeted drug-delivery vehicles, flexible skin-like electronics, high-capacity energy storage systems, and neuromorphic circuits. This review summarizes recent progress in the design, synthesis, and structure–property relationships of these materials, and critically discusses their use in biomedical and electronic applications. Particular attention is given to the convergence of the two fields in bioelectronic interfaces, wearable health monitors, and tissue-integrated devices. Major challenges, including biocompatibility and long-term stability, scalable and reproducible manufacturing, environmental impact, regulatory approval, and cost, are examined. Finally, future perspectives are outlined, covering data-driven materials discovery, sustainable and biodegradable materials, multifunctional and self-healing systems, and personalized, intelligent medical devices.

Keywords: Functional Materials; Nanomaterials; Biomedical Applications; Flexible Electronics; Biosensors; Drug Delivery; 2d Materials; Mxenes; Conducting Polymers; Bioelectronics

Introduction

The development of civilization has often been described through the materials that defined each era, and the present era is increasingly defined by materials that do more than provide structural support. Functional materials are engineered to perform a specific task: conducting or storing charge, converting light or heat into electricity, sensing a chemical or biological analyte, releasing a therapeutic agent on demand, or promoting the regeneration of living tissue. Their performance arises from precisely controlled composition, crystal structure, morphology, surface chemistry, and dimensionality, particularly at the nanoscale, where quantum confinement and high surface-to-volume ratios give rise to behavior that differs markedly from the bulk material [1,2].

Two fields have been especially transformed by these materials. In biomedicine, the early concept of biomaterials as passive and bio-inert substitutes has given way to bioactive and bioresponsive systems that actively interact with cells and tissues [3,4]. In electronics, the pursuit of miniaturization, flexibility, low power consumption, and

energy autonomy has driven the adoption of organic semiconductors, 2D crystals, and hybrid perovskites alongside, and sometimes in place of, conventional silicon [5,6]. The boundary between the two fields is increasingly blurred. Devices such as epidermal sensors, neural probes, and smart implants require materials that satisfy electronic performance criteria and biological compatibility at the same time [7,8].

Although numerous reviews address individual material classes or single application areas, there is a need for an integrated perspective that links material design principles to the requirements of both biomedical and electronic uses. This review therefore (i) outlines the principal classes of advanced functional materials and their key properties, (ii) discusses representative biomedical and electronic applications, (iii) highlights the emerging convergence of these domains, (iv) analyzes the main challenges that hinder clinical and commercial translation, and (v) presents future research directions.

This article is a narrative review. Literature was selected for its influence, mechanistic insight, and relevance to translation, with priority given to landmark reports and authoritative reviews. The emphasis is on conceptual links between material design and device requirements rather than exhaustive coverage of every material or device.

Major Classes of Advanced Functional Materials

Carbon-Based Nanomaterials

Carbon nanomaterials, including graphene, graphene oxide (GO), reduced graphene oxide (rGO), carbon nanotubes (CNTs), carbon dots, and fullerenes, remain among the most widely investigated functional materials. Since the isolation of single-layer graphene, its exceptional electrical conductivity, mechanical strength, thermal conductivity, and large specific surface area have motivated research in transistors, transparent electrodes, sensors, and energy devices [1]. Oxygenated derivatives such as GO and rGO offer tunable surface chemistry that allows covalent and non-covalent functionalization, making them attractive for drug loading, biosensing, and antibacterial coatings. Carbon dots are valued for their photoluminescence, low toxicity, and ease of synthesis from inexpensive precursors, and are used in bioimaging and sensing. Despite these advantages, the properties of carbon nanomaterials depend strongly on synthesis route, layer number, defect density, and functionalization, which complicates reproducibility and toxicological assessment.

Two-Dimensional Materials Beyond Graphene

Transition metal dichalcogenides (TMDs) such as MoS₂ and WS₂ possess thickness-dependent band gaps and strong light-matter interactions, which make them suitable for field-effect transistors, photodetectors, and gas or biomolecule sensors [9]. Hexagonal boron nitride serves as an atomically flat insulating substrate and dielectric. MXenes, a large family of 2D transition metal carbides, nitrides, and carbonitrides first reported in 2011, combine metallic conductivity with hydrophilic, functionalizable surfaces [10,11].

These properties have led to broad exploration in supercapacitors, batteries, electromagnetic interference shielding, photothermal therapy, and biosensors. Black phosphorus and 2D layered double hydroxides further expand the available band gap range and degradability profiles. Key unresolved issues for 2D materials include oxidative stability (notably for MXenes and black phosphorus), large-area uniform

synthesis, and long-term fate in biological environments.

Conducting and Semiconducting Polymers

Since the discovery of electrical conductivity in doped polyacetylene, conjugated polymers have evolved into a versatile class of materials that combine electronic or ionic conduction with mechanical softness and solution processability [12]. Poly(3,4-ethylenedioxythiophene) doped with polystyrene sulfonate (PEDOT:PSS), polypyrrole, and polyaniline are widely used in organic electrochemical transistors, neural electrodes, and biosensors, because their mixed ionic–electronic conduction matches well with aqueous physiological environments [8]. Their modulus is closer to that of tissue than rigid inorganic conductors, reducing mechanical mismatch and inflammatory response at the interface. Current research focuses on improving conductivity and stability under physiological conditions, introducing biodegradability, and developing intrinsically stretchable formulations.

Metal Oxides, Piezoelectrics, and Perovskites

Metal oxides such as TiO₂, ZnO, Fe₃O₄, CeO₂, and indium-based transparent oxides are mainstay functional materials, supporting applications that range from photocatalysis and gas sensing to magnetic resonance contrast and thin-film transistors. ZnO nanostructures exhibit piezoelectric behavior that has been exploited in nanogenerators able to harvest mechanical energy from small movements [13]. Lead-based and lead-free perovskite oxides such as barium titanate are central to piezoelectric sensors, actuators, and capacitors. Halide perovskites, first used as light absorbers in solar cells, have achieved remarkable power-conversion efficiencies and are now investigated in light-emitting diodes, photodetectors, and X-ray detectors [14]. Their sensitivity to moisture, heat, and the toxicity concern associated with lead remain significant barriers, particularly for any use near the human body.

Metal–Organic Frameworks and Covalent Organic Frameworks

MOFs are crystalline porous materials assembled from metal nodes and organic linkers, offering exceptionally high surface areas and tunable pore chemistry [15]. In biomedicine, MOFs are used as carriers with high drug-loading capacity and controlled, pH-responsive release, as well as in imaging and catalytic therapy. In electronics, conductive MOFs and MOF-derived carbons are being studied for chemiresistive sensors, supercapacitors, and electrocatalysis. Covalent organic frameworks (COFs) offer comparable porosity with greater chemical stability due to strong covalent bonding. For both families, hydrolytic stability, scalable synthesis, and film processing are the main practical obstacles.

Stimuli-Responsive Hydrogels and Soft Materials

Hydrogels are water-swollen polymer networks whose similarity to the extracellular matrix makes them natural candidates for tissue engineering, wound dressings, and drug delivery [16]. Stimuli-responsive variants change swelling, stiffness, or permeability in response to temperature, pH, light, electric or magnetic fields, or specific biomolecules. Incorporation of conductive fillers, such as CNTs, graphene, MXenes, or PEDOT, yields conductive hydrogels that are increasingly used as soft electrodes, strain sensors, and electronic skin. Self-healing and adhesive hydrogels have extended

their use to dynamic tissues and wearable interfaces. Challenges involve mechanical robustness, dehydration in open-air devices, and long-term electrical stability.

Bioactive Ccramics, Glasscs, and Mctals

Bioactive glasses and calcium phosphate ceramics, such as hydroxyapatite and tricalcium phosphate, form a bond with living bone through the formation of a carbonated hydroxyapatite layer, a principle established in the early development of bioactive materials [3,17,25]. Today they are processed into porous scaffolds, composites, and coatings, often doped with ions such as strontium, zinc, copper, or magnesium to promote osteogenesis, angiogenesis, or antibacterial action. Biodegradable metals based on magnesium, zinc, and iron are explored for temporary orthopedic and cardiovascular implants that dissolve after healing. Titanium alloys and cobalt–chromium alloys remain the clinical standard for load-bearing implants, but their surfaces are increasingly modified with nanostructures and functional coatings to improve osseointegration and reduce infection.

Synthcsis and Proccssing Stratcgics

The function of a material is inseparable from how it is made. Top-down routes, such as mechanical and liquid-phase exfoliation of layered crystals or etching of MAX phases to obtain MXenes, yield nanosheets from bulk precursors [10,24]. Bottom-up routes, including chemical vapor deposition (CVD), hydrothermal and solvothermal synthesis, sol–gel processing, and electrochemical deposition, build structures atom by atom or molecule by molecule and allow finer control over composition, thickness, and crystallinity. CVD is the principal route to large-area, high-quality graphene and TMD films, whereas hydrothermal and sol–gel methods are widely used for oxides, MOFs, and bioceramics because of their low cost and scalability.

Soft and biological materials are typically processed by solution-based methods. Electrospinning produces nanofibrous scaffolds that mimic the fibrillar extracellular matrix, self-assembly generates ordered nanostructures from block copolymers and peptides, and in situ polymerization yields conductive polymer coatings directly on electrodes. Additive manufacturing, including extrusion, inkjet, and stereolithographic printing, enables patient-specific geometries and multimaterial devices [21]. Surface functionalization with polymers, peptides, antibodies, or aptamers is then used to tune colloidal stability, biological targeting, and interfacial charge transfer. The choice of route involves trade-offs between quality, throughput, cost, and the use of toxic solvents, which are revisited in Section 6.

Structural and Functional Charactcrization

Reliable structure–property relationships depend on thorough characterization. Electron microscopy (SEM, TEM) and atomic force microscopy reveal morphology, thickness, and defects. X-ray diffraction and Raman spectroscopy identify crystal phase, layer number, and strain, while X-ray photoelectron and Fourier-transform infrared spectroscopy establish surface chemistry and functional groups. Dynamic light scattering and zeta potential measurements describe the size distribution and colloidal stability of nanoparticles in physiological media. Electrical performance is assessed by four-point probe, Hall effect, impedance spectroscopy, and transistor characteristics, and

mechanical behavior by tensile and cyclic bending tests. For biomedical use, these data must be paired with cytotoxicity, hemocompatibility, degradation, and in vivo studies carried out in physiologically relevant media rather than in water or buffer alone.

Comparative Overview of Material Classes

Table 1 summarizes the characteristic strengths and limitations of the material classes discussed above.

Table 1. Comparative overview of major functional material classes.

Material class	Key properties	Representative biomedical use	Representative electronic use	Main limitation
Carbon nanomaterials (graphene, CNTs, carbon dots)	High conductivity, large surface area, strength	Biosensing, drug loading, bioimaging	Transparent electrodes, sensors, supercapacitors	Batch variability, toxicity data gaps
2D materials (TMDs, MXenes, h-BN)	Tunable band gap, metallic conductivity (MXenes), hydrophilic surfaces	Photothermal therapy, biosensors	Transistors, photodetectors, energy storage	Oxidative instability, large-area synthesis
Conducting polymers (PEDOT:PSS, polypyrrole)	Mixed ionic–electronic conduction, softness	Neural electrodes, biosensors	Organic electrochemical transistors, flexible circuits	Stability in physiological media, conductivity
Material class	Key properties	Representative biomedical use	Representative electronic use	Main limitation
Metal oxides and perovskites	Piezoelectricity, optical activity, magnetism	Imaging contrast, hyperthermia	Gas sensors, nanogenerators, solar cells	Lead toxicity, moisture sensitivity
MOFs and COFs	Very high porosity, tunable pores	Drug carriers, catalytic therapy	Chemiresistive sensors, electrocatalysis	Hydrolytic stability, film processing

Hydrogels	Tissue-like softness, high water content	Tissue scaffolds, wound dressings	Soft electrodes, electronic skin	Dehydration, mechanical robustness
Bioceramics and biodegradable metals	Bioactivity, osteoconduction, resorbability	Bone repair, temporary implants	Limited (dielectric and piezoelectric roles)	Brittleness, controlled degradation rate

Biomcdical Applications

Drug Dclivcry and Nanomcdicinc

Functional nanomaterials allow therapeutic agents to be protected, transported, and released at a defined site and time. Liposomal, polymeric, mesoporous silica, MOF, and inorganic nanocarriers can improve solubility, prolong circulation, and exploit passive or active targeting of diseased tissue. Stimuli-responsive carriers release their payload in response to the acidic tumor microenvironment, elevated enzyme levels, light, ultrasound, or magnetic fields [18]. Gold nanoshells and related plasmonic or photothermal agents, including 2D materials and MXenes, convert near-infrared light to heat for localized tumor ablation [19]. Magnetic iron oxide nanoparticles support magnetically guided delivery, magnetic hyperthermia, and contrast enhancement in magnetic resonance imaging.

Theranostic systems that combine imaging and therapy in a single platform exemplify the multifunctionality sought in this area. Nevertheless, only a modest fraction of administered nanoparticles typically reaches the target tissue, and clearance, protein corona formation, and long-term accumulation need further study.

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The central aim of tissue engineering is to create scaffolds that guide cells to regenerate functional tissue [4]. Scaffold materials must provide suitable mechanical properties, porosity, degradation kinetics, and biochemical cues. Bone regeneration benefits from bioceramic–polymer composites and bioactive glasses, while cartilage, skin, and nerve repair commonly employ hydrogels and electrospun fibers. Electrically active scaffolds have drawn particular interest since electrical stimulation can influence cell proliferation, differentiation, and alignment, notably in neural, cardiac, and musculoskeletal tissues.

Conductive nanowire and polymer scaffolds have been shown to integrate electronic sensing directly within engineered tissue constructs [20]. Additive manufacturing, including 3D bioprinting, allows patient-specific geometries and spatial control of cells and functional components, and has even enabled the printing of tissue-like structures with integrated electronics [21].

Bioscnsors and Diagnostics

Biosensors couple a biological recognition element, such as an enzyme, antibody, aptamer, or nucleic acid, with a transducer that converts binding into a measurable optical,

electrochemical, or electrical signal. Functional nanomaterials improve sensitivity and selectivity by increasing the active surface area, accelerating electron transfer, and amplifying signals. Graphene, CNT, and MXene electrodes, gold and magnetic nanoparticles, quantum dots, and MOFs have all been integrated in glucose, cardiac biomarker, pathogen, and cancer biomarker sensors. Field-effect transistor and organic electrochemical transistor biosensors enable label-free, real-time detection at very low concentrations [8,9]. Point-of-care and wearable formats that analyze sweat, saliva, tears, or interstitial fluid are advancing noninvasive monitoring, though correlation with blood concentrations, sensor drift, and calibration remain active concerns.

Bioclectronics and Neural Interfaces

Bioelectronic devices record or modulate electrical activity in the nervous system, heart, and muscles. Traditional rigid metal and silicon probes can provoke chronic inflammation and signal degradation owing to mechanical mismatch with soft neural tissue. Conducting polymer coatings, graphene and CNT electrodes, soft hydrogel interfaces, and ultrathin flexible substrates reduce impedance, improve charge injection capacity, and improve long-term recording quality [7,8]. Ultrathin epidermal electronic systems can conform to

the skin to record electrophysiological signals without gels or adhesives [22]. Closed-loop systems that sense physiological signals and deliver stimulation or drugs accordingly are an important direction for treating neurological and cardiovascular conditions.

Antibacterial and Wound-Healing Materials

Antibiotic resistance has intensified the search for materials that combat infection by physical or chemical mechanisms rather than conventional antibiotics. Silver, copper, and zinc oxide nanoparticles, graphene-based materials, cationic polymers, nanostructured surfaces that rupture bacterial membranes, and photothermal or photodynamic agents have shown strong antibacterial activity. Smart dressings combining antibacterial, moisture-regulating, and sensing functions can monitor wound pH, temperature, and moisture, and deliver therapeutics in response. Balancing antimicrobial potency with cytotoxicity toward host cells and with potential environmental release is a continuing challenge.

Medical Imaging and Image-Guided Therapy

Functional nanomaterials also act as contrast and reporter agents that make disease visible at the cellular and molecular level [32]. Superparamagnetic iron oxide nanoparticles and gadolinium-based nanostructures enhance contrast in magnetic resonance imaging, gold and bismuth-based nanoparticles improve X-ray computed tomography, and quantum dots, carbon dots, and upconversion nanoparticles provide bright, photostable fluorescence for optical imaging. Photoacoustic imaging benefits from strongly absorbing materials such as gold nanorods, melanin-like nanoparticles, and MXenes, which also serve as photothermal agents, enabling imaging and therapy to be combined in one platform. Key requirements include colloidal stability in blood, controlled clearance to avoid long-term retention, and surface chemistry that supports targeting while minimizing immune recognition. Multimodal agents that integrate two

or more imaging modes can compensate for the limitations of any single technique, although added complexity makes regulatory evaluation more demanding.

Electronic Applications

Flexible and Wearable Electronics

Flexible electronics require materials that sustain electrical function under bending, stretching, and twisting. Nanowires, CNTs, graphene, MXenes, and conductive polymers deposited on elastomeric substrates have been used in stretchable conductors, strain and pressure sensors, flexible displays, and electronic skin [7,22,26]. Strategies such as serpentine geometries, buckled structures, and intrinsically stretchable composites provide durability under repeated deformation. Soft sensors that detect pulse, respiration, motion, temperature, and sweat biomarkers have moved from laboratory demonstrations toward consumer and clinical wearables, but washability, skin comfort, signal stability, and power supply remain limiting factors.

Energy Harvesting and Storage

Powering miniaturized and wearable devices requires efficient energy storage and harvesting. Lithium-ion batteries remain the dominant technology, and progress in electrode and electrolyte materials continues to improve energy density and safety [23]. Supercapacitors based on porous carbons, graphene, MXenes, and conducting polymers deliver high power density and long cycle life. Flexible and fiber-shaped storage devices are being developed for textile integration. On the harvesting side, piezoelectric and triboelectric nanogenerators convert body movement into electricity [13], thermoelectric materials exploit temperature gradients between the body and environment, and perovskite and organic photovoltaics supply flexible solar power [14]. Self-powered sensors that combine harvesting and sensing are especially attractive for implantable and wearable systems, although output power, stability, and encapsulation must be improved.

Sensors and Optoelectronics

Functional materials underpin gas, humidity, temperature, pressure, and optical sensors across healthcare, environmental monitoring, and industry. Metal oxide semiconductors and 2D materials are widely used in chemiresistive gas sensors, while 2D semiconductors and perovskites provide high-responsivity photodetectors [9,14]. Quantum dots and perovskite nanocrystals offer narrow emission and tunable color for displays and lighting. In biomedicine, optoelectronic components enable pulse oximetry, photoplethysmography, and optogenetic stimulation, again highlighting the overlap between electronic and biomedical requirements.

Memory, Neuromorphic, and Next-Generation Computing Devices

Resistive switching in metal oxides, 2D materials, and organic systems has enabled memristors and non-volatile memory with low energy consumption. Such devices can emulate synaptic behavior, offering a route toward neuromorphic hardware that processes information in a brain-inspired, energy-efficient way. Organic electrochemical transistors with ionic gating are particularly promising for interfacing artificial synapses with biological systems. Atomically thin semiconductors are also explored for scaling transistors beyond the limits of silicon. Variability, endurance, and integration density

remain the key hurdles before commercial adoption.

Biodegradable and Sustainable Electronics

The growing volume of short-lived wearable and disposable medical electronics has drawn attention to the end-of-life of electronic materials. Transient electronics are built from materials that dissolve or resorb in a controlled manner, for example ultrathin silicon, magnesium and zinc conductors, and silk or poly(lactic-co-glycolic acid) substrates, so that a device can perform a diagnostic or therapeutic task and then disappear [27]. In parallel, naturally derived and bio-based materials, including cellulose, silk fibroin, chitosan, gelatin, and melanin, are being explored as substrates, dielectrics, and even semiconductors for environmentally friendly devices [28]. These approaches reduce electronic waste and the need for retrieval surgery, but their lifetime must be tuned precisely: degradation that is too fast compromises function, while degradation that is too slow defeats the purpose. Standardized methods to measure degradation kinetics and to evaluate the safety of degradation products are still lacking.

Convergence of Biomedical and Electronic Functionality

The most exciting developments occur where the demands of electronics and biology are addressed simultaneously. Biointegrated electronics must be thin, soft, conformal, and water-stable, and often wirelessly powered. Examples include epidermal patches that monitor biochemical and physiological signals concurrently, smart contact lenses, ingestible sensors, electronic scaffolds that monitor and stimulate regenerating tissue, and soft neural implants for brain-machine interfaces [7,20,22]. Transient electronics, designed to dissolve safely in the body after a defined period, avoid secondary extraction surgery and rely on biodegradable conductors, dielectrics, and encapsulants. Material selection in this domain is a multi-objective optimization problem in which conductivity, mechanical compliance, biocompatibility, stability, processability, and cost must be

balanced, and no single class of materials currently satisfies every criterion. Composites and hybrid systems, for example conductive polymer-MXene hydrogels or graphene-bioceramic scaffolds, therefore represent a pragmatic path forward.

Challenges

Biocompatibility, Toxicity, and Long-Term Safety

Many nanomaterials display size-, shape-, and surface-dependent toxicity, and their biodistribution, degradation products, and chronic effects are incompletely understood. Standardized in vitro assays frequently fail to predict in vivo behavior, and long-term implantation data remain scarce. Rigorous characterization of material identity, purity, and surface chemistry, together with comprehensive biodegradation and immunological studies, is needed.

Stability and Reliability

Devices must remain functional in warm, ionic, enzyme-rich, and mechanically dynamic environments for months or years. Oxidation of MXenes, degradation of perovskites, delamination of coatings, biofouling of sensors, and fatigue of stretchable conductors all limit lifetime. Effective, thin, biocompatible encapsulation is still an unsolved problem

for many implantable systems.

Scalable, Reproducible, and Cost-Effective Manufacturing

Laboratory-scale synthesis often yields high-performing materials in small quantities that are difficult to reproduce at industrial scale. Batch-to-batch variability in size distribution, defects, and functionalization undermines device reliability. Roll-to-roll printing, inkjet and aerosol jet printing, and continuous-flow synthesis are promising, but quality control and cost remain concerns.

Regulatory, Ethical, and Clinical Translation

Materials that combine drug, device, and electronic functions face complex regulatory pathways. The absence of harmonized standards for nanomaterial characterization and testing slows approval, and the gap between promising preclinical results and clinical adoption remains wide. Data security, privacy, and equitable access are additional ethical considerations for connected medical devices.

Environmental Sustainability

The use of critical or toxic elements (such as lead, cobalt, and indium), energy-intensive synthesis, and electronic waste from short-lived wearable devices raise sustainability concerns. Life-cycle assessment and green synthesis should be integral parts of material development rather than afterthoughts.

Interdisciplinary Integration

Progress requires close collaboration between materials scientists, chemists, engineers, biologists, clinicians, and regulatory experts. Differences in terminology, performance metrics, and testing protocols between disciplines can hinder reproducibility and comparison across studies, making standardized reporting guidelines highly valuable.

Future Perspectives

Data-driven and AI-assisted materials discovery. Machine learning, high-throughput computation, and automated (self-driving) laboratories can accelerate the identification and optimization of materials, predict toxicity and stability, and reduce the cost of trial-and-error experimentation. Reliable open datasets and standardized reporting are prerequisites.

Sustainable and biodegradable materials. Natural polymers such as cellulose, silk, chitosan, and gelatin, together with biodegradable conductors and green synthesis routes, will support transient implants and environmentally responsible consumer electronics.

Multifunctional, self-healing, and adaptive systems. Materials that sense, process, and respond within a single architecture, while repairing damage autonomously, will extend device lifetime and enable true closed-loop therapy.

Personalized and intelligent medicine. Combining patient-specific 3D-printed constructs, wearable and implantable sensing, and data analytics can support individualized diagnosis and treatment, with continuous monitoring supporting preventive healthcare.

Next-generation power solutions. Self-powered, battery-free, and wirelessly powered devices that harvest energy from the body, light, or radiofrequency fields will

remove one of the largest barriers to long-term implantable and wearable use.

Standardization and translational frameworks. Common testing protocols, early engagement with regulators, and scalable manufacturing strategies will be needed to turn laboratory innovations into approved products, particularly for low- and middle-income regions where affordable diagnostics can have major public health impact.

Kcy™csearch Gaps

Several gaps stand out across the literature and define priorities for future work.

Long-term in vivo data. Most studies report weeks of performance, whereas clinical devices must operate for years. Long-duration studies in relevant large-animal models are needed.

Delivery efficiency. Analyses of nanoparticle delivery to tumors show that only a small fraction of the administered dose reaches the target, which points to the need for better targeting and a deeper understanding of biological barriers [30,31].

Standardized reporting. Studies often use different media, concentrations, and metrics, which prevents fair comparison. Minimum reporting standards for material characterization, biological testing, and device performance would improve reproducibility.

Predictive models. Machine learning has shown value for predicting material properties [29], but its use for biocompatibility, degradation, and long-term device reliability remains limited by the scarcity of high-quality, shared data.

Manufacturing translation. Few promising laboratory materials have a defined pathway to scalable, quality-controlled production under regulatory standards.

Conclusion

Advanced functional materials have transformed the possibilities of biomedical and electronic technologies. Carbon nanomaterials, 2D crystals, conducting polymers, metal oxides, perovskites, MOFs, hydrogels, and bioactive ceramics each contribute unique properties, and their combination in hybrid and composite systems is producing devices with unprecedented functionality, from targeted nanomedicines and regenerative scaffolds to skin-like sensors and neuromorphic circuits. The principal obstacles are no longer limited to demonstrating performance in the laboratory; they involve long-term safety, stability in physiological environments, reproducible large-scale manufacturing, regulatory acceptance, and sustainability. Addressing them will require integrated, interdisciplinary research that couples molecular-level material design with device

engineering, rigorous biological evaluation, and responsible manufacturing. With such an approach, functional materials are well positioned to underpin the next generation of intelligent, personalized, and sustainable healthcare and electronic systems.

™cferences

Geim AK, Novoselov KS. The rise of graphene. *Nat Mater*. 2007;6:183–191.

Mitragotri S, Lahann J. Physical approaches to biomaterial design. *Nat Mater*. 2009;8:15–23.

Hench LL, Splinter RJ, Allen WC, Greenlee TK. Bonding mechanisms at the interface of ceramic prosthetic materials. *J Biomed Mater Res*. 1971;5:117–141.

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- Langer R, Vacanti JP. Tissue engineering. *Science*. 1993;260:920–926.
- Goodenough JB, Park KS. The Li-ion rechargeable battery: a perspective. *J Am Chem Soc*. 2013;135:1167–1176.
- Wang QH, Kalantar-Zadeh K, Kis A, Coleman JN, Strano MS. Electronics and optoelectronics of two-dimensional transition metal dichalcogenides. *Nat Nanotechnol*. 2012;7:699–712.
- Someya T, Bao Z, Malliaras GG. The rise of plastic bioelectronics. *Nature*. 2016;540:379–385.
- Rivnay J, Inal S, Salleo A, Owens RM, Berggren M, Malliaras GG. Organic electrochemical transistors. *Nat Rev Mater*. 2018;3:17086.
- Radisavljevic B, Radenovic A, Brivio J, Giacometti V, Kis A. Single-layer MoS₂ transistors. *Nat Nanotechnol*. 2011;6:147–150.
- Naguib M, Kurtoglu M, Presser V, et al. Two-dimensional nanocrystals produced by exfoliation of Ti₃AlC₂. *Adv Mater*. 2011;23:4248–4253.
- Gogotsi Y, Anasori B. The rise of MXenes. *ACS Nano*. 2019;13:8491–8494.
- Chiang CK, Fincher CR, Park YW, et al. Electrical conductivity in doped polyacetylene. *Phys Rev Lett*. 1977;39:1098–1101.
- Wang ZL, Song J. Piezoelectric nanogenerators based on zinc oxide nanowire arrays. *Science*. 2006;312:242–246.
- Kojima A, Teshima K, Shirai Y, Miyasaka T. Organometal halide perovskites as visible-light sensitizers for photovoltaic cells. *J Am Chem Soc*. 2009;131:6050–6051.
- Furukawa H, Cordova KE, O'Keeffe M, Yaghi OM. The chemistry and applications of metal–organic frameworks. *Science*. 2013;341:1230444.
- Peppas NA, Hilt JZ, Khademhosseini A, Langer R. Hydrogels in biology and medicine: from molecular principles to bionanotechnology. *Adv Mater*. 2006;18:1345–1360.
- Kokubo T, Takadama H. How useful is SBF in predicting in vivo bone bioactivity? *Biomaterials*. 2006;27:2907–2915.
- Mura S, Nicolas J, Couvreur P. Stimuli-responsive nanocarriers for drug delivery. *Nat Mater*. 2013;12:991–1003.
- Hirsch LR, Stafford RJ, Bankson JA, et al. Nanoshell-mediated near-infrared thermal therapy of tumors under magnetic resonance guidance. *Proc Natl Acad Sci USA*. 2003;100:13549–13554.
- Tian B, Liu J, Dvir T, et al. Macroporous nanowire nanoelectronic scaffolds for synthetic tissues. *Nat Mater*. 2012;11:986–994.
- Mannoor MS, Jiang Z, James T, et al. 3D printed bionic ears. *Nano Lett*. 2013;13:2634–2639.
- Kim D-H, Lu N, Ma R, et al. Epidermal electronics. *Science*. 2011;333:838–843.
- Armand M, Tarascon J-M. Building better batteries. *Nature*. 2008;451:652–657.
- Novoselov KS, Geim AK, Morozov SV, et al. Electric field effect in atomically thin carbon films. *Science*. 2004;306:666–669.
- Hench LL, Polak JM. Third-generation biomedical materials. *Science*. 2002;295:1014–1017.
- Chortos A, Liu J, Bao Z. Pursuing prosthetic electronic skin. *Nat Mater*. 2016;15:937–950.
- Hwang S-W, Tao H, Kim D-H, et al. A physically transient form of silicon electronics. *Science*. 2012;337:1640–1645.

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Print ISSN

3007-3189

<http://amresearchreview.com/index.php/Journal/about>

- Irimia-Vladu M. "Green" electronics: biodegradable and biocompatible materials and devices for sustainable future. *Chem Soc Rev.* 2014;43:588–610.
- Butler KT, Davies DW, Cartwright H, Isayev O, Walsh A. Machine learning for molecular and materials science. *Nature.* 2018;559:547–555.
- Peer D, Karp JM, Hong S, Farokhzad OC, Margalit R, Langer R. Nanocarriers as an emerging platform for cancer therapy. *Nat Nanotechnol.* 2007;2:751–760.
- Wilhelm S, Tavares AJ, Dai Q, et al. Analysis of nanoparticle delivery to tumours. *Nat Rev Mater.* 2016;1:16014.
- Weissleder R, Pittet MJ. Imaging in the era of molecular oncology. *Nature.* 2008;452:580–589.