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TOPICAL REVIEW

2D material-based sensing technology innovation roadmap for biomedical applications

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Abstract

Two-dimensional materials (2MD) have emerged as a transformative platform for biomedical sensing owing to their unique properties. Over the past decade, 2DM, such as graphene and MXenes have enabled sensing concepts with the potential to surpass the sensitivity, speed, and miniaturization limits of conventional technologies. When combined with other innovative materials such as aptamers or magnetic nanoparticles (MNPs), a range of components can be developed. From electrochemical electrodes and field effect transistor channels to conductive inks and triboelectric nanogenerators, these components offer a variety of biomedical applications that have the potential to revolutionize healthcare. This Roadmap reviews the current state of 2DM-based biomedical sensing within four EU-funded Horizon Europe projects under the Graphene Flagship, identifies key scientific and technological barriers, and outlines priority research directions for the short (2027) and mid-term (2030) future. The analysis focuses on the materials, various components comprising these materials, and several biomedical applications that are currently being researched within the overall biomedical focus of the Graphene Flagship Initiative. By consolidating expert perspectives from the four consortia, this roadmap aims to guide coordinated efforts to accelerate the transition of 2DM from laboratory demonstrations to robust, scalable, and impactful biomedical sensing technologies.

1. Introduction

Biomedical sensing underpins modern healthcare and enables disease diagnosis, patient monitoring, and personalized treatment strategies. The growing demand for reliable, rapid, sensitive, and low-cost sensing solutions has exposed the limitations of conventional materials, particularly when ultralow detection limits, real-time operation, or device miniaturization are required. Two-dimensional materials (2DM), defined by their layered structures with thicknesses down to a single atomic layer, offer a fundamentally different material platform that is well-suited to address these challenges.

These materials exhibit properties that are highly attractive for biomedical sensing, including high carrier mobility, strong light–matter interactions, mechanical flexibility, and surfaces that can be chemically engineered for selective bio-recognition. As a result, 2DM have enabled sensing modalities spanning electrochemical, field-effect, optical, piezoelectric, and multimodal approaches, with applications in the detection of biomarkers, pathogens, metabolites, and physiological signals.

Despite this progress, most 2DM-based biomedical sensors remain in the proof-of-concept stage. Challenges related to material reproducibility, long-term stability in biological environments, scalable fabrication, and regulatory compatibility continue to hinder the translation beyond the laboratory. In this context, roadmap articles play a critical role in synthesizing collective knowledge, identifying consensus challenges, and outlining realistic developmental pathways. This Roadmap focuses on 2DM-based biomedical sensing, with the objective of providing a structured outlook on where the field stands today and where coordinated research efforts are needed to achieve a practical impact over the coming decade.

2. Methodology

2.1. Innovation interface investigations (3I)

This Roadmap followed the 3I methodology (figure 1) developed in the context of the Graphene Roadmap Briefs of the Graphene Flagship [1], incorporating certain variations. Instead of the proposed sequence of four consecutive stages (Conception, Consultation, Interactive Workshop and Complementary Innovation Research), we performed the activity in three stages as follows:

The focus investigations under the Conception Stage were tied to 2DM applications within the four EU-funded Research and Innovation Action projects under the Graphene Flagship that developed a range of sensing technologies for biomedical applications: 2D-BioPAD [2], MUNASET [3], GRAPHERGIA [4] and SAFARI [5]. Each of the four projects consists of consortia with deep knowledge and understanding of the innovation spheres and interfaces between them, which allowed to collect further key information (see table 1) during the Consultation stage. The consultation followed several iterations, either individually (for clarifications and extensions) or collectively, so that all experts could provide constructive feedback across all the information collected. Finally, the Complementary Desk Research stage was executed in parallel, to complement gathered knowledge.

After all iterations were completed, the information was aggregated and presented in the following sections per innovation sphere. Finally, high-level Strengths, Weaknesses, Opportunities, and Threats (SWOT) analysis and value chain analysis for the analyzed 2DM for biomedical applications are elaborated, followed by a schematic overview of the overall roadmap until 2030.

3. Materials

3.1. Graphene

Graphene is a two-dimensional (2D) material consisting of a single layer of carbon atoms arranged in a honeycomb lattice. The combination of high carrier mobility, mechanical robustness, thermal conductivity, and large accessible surface area makes it a cornerstone material in the 2D-materials ecosystem for biomedical devices, particularly where ultrathin transduction layers, high interfacial charge sensitivity, and robust electrode architectures are required.

Graphene is exceptionally light (areal mass density $\approx$ 0.77 mg m^{-2}), mechanically stiff (Young's modulus $\sim$1 TPa) with high intrinsic strength (reported tensile strength $\sim$130 GPa), and highly thermally conductive (often reported in the $\sim 10^3$–10^4 W m^{-1} K^{-1} range depending on measurement conditions and sample quality). Its electronic structure is semi-metallic (zero bandgap) with very high intrinsic mobility (more than 200 000 $cm^2 \cdot V^{-1} \cdot s^{-1}$) in pristine suspended samples. In practice, these properties are strongly dependent on the material quality (defects and grain boundaries), processing history, surface chemistry, and dispersion state, which are critical for biomedical applications.

Importantly, 'graphene' in biomedical literature often refers to a family of graphene-related materials (GRMs), including few-layer graphene and chemically modified derivatives such as graphene oxide (GO) (see section 3.2) and reduced graphene oxide (rGO) (see section 3.3). GO carries oxygen-containing functional groups (e.g. hydroxyl, epoxy, carbonyl, and carboxyl), which enhance water dispersibility and provide versatile coupling chemistry for (bio)molecules; reduction toward rGO partially

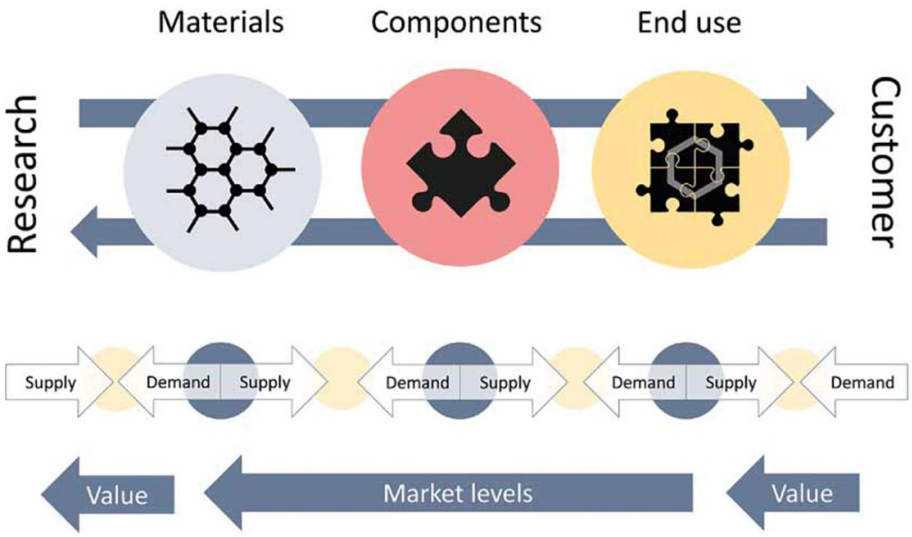

Figure 1. Generalized value chain-based approach for a Technology Innovation Roadmap following the 3I methodology. Reproduced from [1]. © The Author(s). Published by IOP Publishing Ltd. CC BY 4.0.

Table 1. Conception stage template for the materials innovation sphere to collect information from experts during the consultation stage.

Sphere	Interface aspect	Description
Materials	Material	Briefly list and describe the 2D Materials (graphene, MXenes, etc) and other key materials that are needed by a biosensor component to function. For each material, fill in the following 'columns'
	Function	What are the main properties of the material?
	Tools	What tools do you use to synthesize, characterize, optimize, etc this material (physical and digital tools)?
	Output—Component(s)	What is the offering of this material for the component that it will be used for?
	Roadblocks/Barriers	What are your main barriers with this material. What are you struggling with?
	Alternatives	What are the current alternatives to this material in the market now?
	Tech evolution 2027	How do you expect this material to evolve in the next 2 years? Quantify, if possible, based on its properties.
	Tech evolution 2030	How do you expect this material to evolve in the next 5 years? Quantify, if possible, based on its properties.
	Current market (2025)	What is the current market size for this material in Europe and Globally?
	Future market (2027)	What is the expected market size/growth for this material in Europe and Globally in the next 2 years?
	Future market (2030)	What is the expected market size/growth for this material in Europe and Globally in the next 5 years?
	Current cost (2025)	What is the average current cost (per unit) for this material in the market right now?
	Future cost (2027)	What is the expected cost (per unit) for this material in 2 years?
	Future cost (2030)	What is the expected cost (per unit) for this material in 5 years?

restoring the electrical conductivity while decreasing the oxygen content and solubility.

In practice, 'graphene' often refers to a family of materials ranging from pristine graphene and few-layer graphene (typically <10 layers) to graphene nanoplatelets/flakes and graphene nanoribbons. Graphene/GRMs appear as (i) continuous monolayer or few-layer films, (ii) patterned channels (e.g. ribbons or vertically oriented layers), (iii) porous/foam-like architectures, (iv) printed or coated flake networks (inks), and (v) composite coatings. These forms are applied and valorized for core applications such as conductive coatings, field-effect transistors (FETs), electrodes in batteries/supercapacitors, transparent conductive films, biomedical engineering (bone/nerve scaffolds and regenerative constructs), membranes for water treatment and antibacterials, and multifunctional therapeutic and diagnostic platforms (drug delivery systems and biosensors).

Pristine graphene synthesis routes determine its domain size, defect density, contamination profile, and surface chemistry. For electronics-grade platforms bottom-up film growth techniques such as chemical vapor deposition (CVD) on catalytic metals (commonly Cu or Ni) remain the leading approach for large-area monolayer graphene, with substantial control over layer number and crystallinity (density of defects and domain size) [6]. Cu tends to

favor monolayer growth due to low carbon solubility, whereas Ni more readily yields multilayers through carbon dissolution/precipitation during cooling. Epitaxial graphene on SiC delivers wafer-scale, high-crystallinity graphene but at high temperatures and cost, with substrate constraints that limit general scalability. For biomedical devices, the major practical hurdles are not only growth but transfer and patterning. Conventional lithography/etch/transfer workflows can introduce defects, residues, and alignment errors that degrade device performance and reproducibility [7].

On the other hand, top–down exfoliation is often utilized for scalable inks and coatings. Liquid-phase exfoliation (LPE) remains the workhorse for scalable pristine graphene production in dispersions suitable for printing and coating. LPE separates graphite into thinner pristine graphene sheets by dispersing graphite in a suitable solvent and applying forces, such as ultrasonication or mechanical agitation, such as DMF, water, ethanol, and other organics, and the solvent must adequately stabilize exfoliated flakes [7]. LPE is operationally simple and scalable, but produces distributions in flake size/layer number and may introduce solvent/surfactant residues, which are factors that must be controlled for biomedical QA/QC.

In addition to the aforementioned conventional methods, direct laser processing has emerged as a solvent-free, digitally controlled method to produce pristine graphene films. Two prominent approaches are the direct laser scribing of pristine graphene on the surface of a carbon-containing precursor (polymer, biomass, or carbides) and the newly developed laser-assisted explosive synthesis and transfer (LEST) of pristine grapheme [8]. The LEST method enables graphene synthesis from a carbon precursor using a pulsed laser, and simultaneously transfers and deposits it onto a nearby acceptor substrate. This process can yield high-purity, few-layer turbostratic graphene with a C/O ratio of approximately 30 and a high sp2 carbon content. Compared to CVD, laser processing allows one-step synthesis and patterning on flexible substrates without chemical etchants. Therefore, careful material definition and characterization are essential when comparing biomedical studies and designing application-ready platforms [9].

3.1.1. Roadblocks/barriers

A few challenges in biomedical technologies constrain their translation into real-world applications. These are a set of materials, processes, and regulatory bottlenecks that collectively limit reproducibility, manufacturability, and clinical adoption. There are cost, yield, and scale–quality trade-offs. High-performance pristine graphene (especially continuous monolayers) typically relies on high-temperature growth and tightly controlled process windows, whereas scalable routes (e.g. bulk/ink approaches) introduce large variability in flake size, thickness, and defect density. This fundamental trade-off complicates the move from 'best-in-class' lab samples to robust high-yield manufacturing lots [6, 7].

Transfer, contamination, and residues are other major barriers. For CVD-derived pristine graphene, transfer and patterning remain the major bottlenecks. Multi-step lithography/etch/transfer workflows can introduce defects, contamination, wrinkles, and alignment issues, thereby reducing throughput and increasing cost [6]. Polymer-assisted transfers (e.g. PMMA supports) are widely used, but the incomplete removal of polymer residues is a recognized degradation mechanism for the film quality and device performance [10]. In addition, catalyst/metal-related residues and process chemicals can be problematic for biomedical use, where trace impurities that can leach out must be controlled.

Batch-to-batch variability and metrology issues are also intrinsic to graphene's applications in biomedical studies, which often span a wide family (pristine monolayer graphene, defective graphene, few-layer graphene, nanoplatelets, GO, and rGO). Small changes in the layer number, lateral size distribution, disorder/defects, and surface chemistry can materially change the electrical properties, dispersibility, and biological response. This makes specification and comparability a central barrier, particularly for multisite studies and regulated manufacturing [11].

International standards have addressed this gap. For instance, ISO provides (a) terminology for graphene and related 2DM (ISO/TS 80004-13:2024), (b) a matrix linking key properties to measurement techniques (ISO/TR 19733:2019), and (c) guidance for the structural characterization of graphene powders/dispersion-derived materials (ISO/TS 21356-1:2021). For example, wafer-scale integration is a decisive bottleneck for graphene sensors; yield is often limited not by the sensing mechanism itself but by wafer-level non-uniformities (e.g. sheet resistance gradients, tears/wrinkles from transfer, polymer residues, and local contamination that change the baseline conductivity and functionalization density). Consequently, roadmapping for biomedical graphene sensors should explicitly treat wafer-scale metrology and process control (mapping of electrical uniformity, defect density, and surface cleanliness) as co-equal to biochemical assay optimization because they dominate drift, calibration burden, and lot-to-lot comparability in clinical workflows [12].

Stability, shelf life, and applicability in real-world operating environments are important cornerstones of the roadmap for graphene. Long-term stability is frequently undercharacterized relative to the intended biomedical duty cycle and storage processes. Drifts

in material properties during storage (humidity/oxygen/light), changes in dispersions (aggregation/sedimentation), and degradation under use conditions (biofluids, mechanical wear, and sterilization/cleaning procedures) can shift performance and safety profiles over time. For commercial viability, these must be addressed using validated packaging, encapsulation, and aging protocols tied to the clinically relevant endpoints [13].

Biocompatibility, distribution, and safety are critical biomedical barriers. The toxicity/biological response of graphene is not a single material constant; it depends strongly on the dimensions, number of layers, and (for oxidized derivatives) surface chemistry such as the carbon–oxygen ratio [8]. This variability motivates 'safety-by-design' material selection and the need for standardized evaluation frameworks and databases to support translation at scale [7].

For clinical or near-clinical deployment, graphene platforms require standardization and regulatory pathways. The materials must be supported by harmonized material definitions, validated test methods, and regulatory-grade documentation (CMC-style control of composition/impurities, stability, and performance). Regulatory agencies provide nanotechnology-related guidance (e.g. FDA guidance collection on products involving nanotechnology [14] and drug/biological products that contain nanomaterials [15]), but graphene-specific clinical precedents remain limited, so the burden of evidence often falls on rigorous characterization, risk assessment, and quality systems.

3.1.2. Technology evolution

By 2027, the most significant progress is expected in manufacturing controllability and integration rather than in isolated performance records. For film-based graphene, roll-to-roll methods, exfoliation techniques, and advanced CVD variants (including cold-wall designs targeting lower energy consumption and higher throughput) continue to mature toward industrial-scale electronic-grade production [16, 17]. In parallel, the field is moving to reduce the long-standing penalty imposed by multistep lithography/transfer/patterning, which can introduce defects, contamination, and alignment losses—key reasons throughput and cost remain challenging for high-performance graphene devices [6]. This has accelerated interest in transfer-minimized or transfer-free integration and 'direct-write' concepts (laser/beam—or reaction-mediated transformations) that aim to shorten process flows, even if resolution, reproducibility, and platform compatibility still limit what can be scaled today In fact, according to current expectations, roll-to-roll production is expected to scale up, leading to a cost reduction of approximately 50%. At the same time, life cycle analysis of laser-induced graphene shows that laser energy dominates environmental impacts [18], and future advances should focus on energy efficiency and renewable power.

Equally important, graphene is entering a phase of stronger metrology and specification disciplines (i.e. through the respective ISO standards). By ∼2027, the practical evolution is likely to be less about 'new standards appearing' and more about wider adoption of these standards in procurement specs, inter-lab comparability studies, and quality control workflows for biomedical-grade graphene components. Finally, artificial intelligence (AI)-enabled pipelines are expected to become routine in graphene R&D and manufacturing, not just for material discovery, but also for process optimization, in-line defect/-contamination detection, and accelerated design-of-experiments, especially as laboratories integrate high-throughput characterization with ML-driven control loops [19].

In the midterm (2027–2030) convergence into integrated biomedical systems is anticipated as part of system-level maturation. Graphene components (films, patterned conducting surfaces, porous graphene architectures) are more often delivered as qualified subsystems, such as flexible electrodes/interconnects, conformal biointerfaces, and robust coatings, rather than custom-made, lab-derived materials. In wearable and soft bioelectronics, graphene-based textile/printed electrodes and porous graphene platforms (including laser-induced graphene) have already been reviewed as credible routes to multifunctional, flexible healthcare devices, suggesting a near-term pathway in which manufacturability and skin/interface robustness can outpace more complex molecular diagnostics in real-world applications [20, 21]. In this horizon, AI is likely to contribute most visibly through (i) automated signal-quality assurance and drift compensation, (ii) improved multiplexing strategies at the device-and-algorithm co-design level, and (iii) data-driven personalization for longitudinal monitoring, contributing to more robust system engineering [19].

By 2030, the trend will continue a downward movement of clinically relevant detection limits and improved multiplexing, driven by the integration and synergy optimization of materials, packaging, electronics, and analytics) [22]. Biosensors are expected to have detection thresholds in the aM (attomolar) range, making them ideal for sensing analytes with low concentrations in bodily fluids that are easier to extract (urine, sweat, saliva, etc).

3.1.3. Market & costs

The global graphene market size is estimated to be approximately USD 196 million by 2023 and is projected to reach USD 1,6 billion by 2030, growing at a CAGR of 35.1% from 2024 to 2030 [23, 24]. Interestingly, graphene oxides dominated the market

and accounted for a revenue share of 47.0% in 2023, with electronics being the main domain of interest.

The use of graphene in biosensors and medical diagnostics, in particular, is estimated to be USD 77.6 million in 2025. With a growth rate of 27.5%, this market is expected to reach approximately USD 126.1 million by 2027 and USD 261.5 million by 2030.

In terms of cost, methods such as CVD, which produce high-quality, high-purity graphene, are generally more expensive than LPE or the reduction of graphene oxide [25]. Currently, graphene powder costs approximately 100–300€ g^{-1}, with high-quality graphene exceeding 1000€ g^{-1}. Projections indicate approximately 50€ per gram of graphene by 2027, a cost that might drop to 10€ per gram in the next 5 years (2030).

3.2. Graphene oxide (GO)

Graphene's rich surface chemistry enables a family of GRMs, among which GO and rGO are the most widely used, because they offer a tunable balance between aqueous processability, chemical functionality, and electrical behavior [26]. GO is typically produced by oxidative intercalation/exfoliation of graphite, yielding a non-stoichiometric 2D sheet in which the conjugated sp^2 carbon network is disrupted by oxygen-containing functionalities; rGO is obtained by partial removal of these oxygen groups via chemical, thermal, electrochemical, or other reduction routes [27].

At the molecular level, the widely used structural picture of GO involves epoxy and hydroxyl groups on the basal planes with carbonyl/carboxyl functionalities enriched at the edges and defect sites, with relative populations that vary strongly with the synthesis history and oxidation extent [28]. This functionalization makes GO hydrophilic and readily dispersible in water and provides abundant handles for covalent coupling (e.g. carboxyl chemistry) and non-covalent interactions (π–π, electrostatic, and H-bonding) that are central to biointerfaces and composite design [8].

Oxidation also alters the electronic structure of graphene. GO is commonly described as electrically insulating/poorly conducting compared to graphene because oxidation fragments the delocalized π-network; its effective bandgap and conductivity can be tuned by adjusting the oxygen content and chemical modification [29]. In electrochemical sensing, GO is particularly appealing because of its large surface area, and oxygen-containing functional groups (which are inevitably introduced during oxidation) enable specific interactions with analytes and provide abundant sites for conjugation with biocomponents [30]. However, extensive oxidation renders GO highly resistive, and conductivity must be partially restored for efficient electrochemical transduction [31].

From a production standpoint, classical Hummers-type chemistries remain common; however, there is clear momentum toward greener and more controllable oxidation/exfoliation routes. For example, a recent review highlights an electrochemical 'liquid membrane electrolysis' approach that enables industrially oriented synthesis of uniform single-layer GO at high yields and at a reported fraction of the cost of traditional Hummers processing, alongside other scalable concepts such as ball-milling oxidation and industrial thermal expansion routes for exfoliation [7]. These advances are particularly relevant for biomedical translation, where batch consistency in oxidation level, lateral size distribution, and impurity profile is often as important as peak material performance. In biomedical applications, GO is valued less as a 'graphene-like conductor' and more as a chemistry-rich 2D scaffold because its oxygenated surface supports dense biofunctionalization, stable dispersion/processing, and robust formation of nanocomposites (including nanoparticle anchoring for optical/magnetic functionalities). GO/graphene derivatives have also been widely explored as drug carriers (leveraging their high surface area and π–π interactions with aromatic therapeutics) and photothermal agents when suitably functionalized (e.g. PEGylated graphene oxide showing passive tumor accumulation and NIR-triggered heating in animal models), underscoring their 'theranostic' relevance beyond sensing [32]. More broadly, authoritative reviews emphasize that graphene derivatives (including GO/rGO) form a major class of nano-biomaterials for imaging/therapy, while also noting that biological outcomes depend strongly on size, morphology, and chemical structure, motivating careful material definition in biomedical studies.

3.2.1. Roadblocks/barriers

The biggest barriers to the use of GO in biosensing are its low conductivity, poor reproducibility between batches, uncertain biocompatibility, and lack of standardized specifications. In addition, there are concerns regarding environmental/-chemical hazards during production (strong oxidants, acidic waste), as well as long-term instability in physiological conditions (potentially altering sensing performance). Current commercial GO products vary widely in quality, with high-purity GO used for biosensing being relatively expensive. Thus, the translation of GO research into regulated biomedical products is mainly limited by reproducibility, characterization, and safety/quality assurance across the full lifecycle, involving manufacture, formulation, sterilization/use, and disposal [33].

GO faces fundamental limitations stemming from its chemistry and structural evolution during synthesis and reduction. Oxidation, which enables large-scale production and dispersibility, inherently

disrupts the sp^2 carbon lattice by introducing a high density of oxygen-containing functional groups. Although the reduction process can remove a portion of the oxygen functionalities and partially restore the electrical conductivity, the original lattice order cannot be fully recovered. The resulting reduced graphene oxide retains a substantial number of defects, disordered regions, and altered bonding configurations, leading to inferior carrier mobility and inconsistent material performance. Even rapid, localized reduction methods that improve conductivity do so at the expense of further lattice distortion rather than true structural healing. As a result, graphene oxide is inherently limited as a replacement for pristine graphene in applications that demand high crystallinity, uniform electronic properties, and defect-free transport behavior. Therefore, its utility is constrained to applications in which processability, surface functionality, and defect-related activity are advantageous, rather than those requiring the intrinsic performance of ideal graphene [11].

In practice, the film resistivity can vary by more than two orders of magnitude across commercial GO sources, reflecting broad disparities in the oxidation degree, defect density, thickness, and residue content. The performance of GO is also highly sensitive to processing history (e.g. drying/rehydration, pH adjustment, ionic strength), which complicates benchmarking across laboratories and suppliers, as well as robust integration with reproducible results in biomedical devices.

Multiple studies have shown that commercial GO is not a single material class, but a wide distribution of nanoforms with different O/C ratios, flake thickness/size distributions, functional group populations, and contamination levels, to the extent that different analytical methods can disagree because of sample heterogeneity. In a large comparative assessment of commercial GO, only a small subset of samples met the basic expectations for stability and label claims, while many contained high metallic residues and other additives introduced by the synthesis and workup. Such variability directly undermines the reproducibility of biomedical devices, where surface chemistry governs protein adsorption, cellular responses, and (in biosensors) signal transduction [34, 35].

Most industrial GO is still derived from graphite oxidation routes (often 'modified Hummers'-type chemistries), which require stringent control of reaction temperature, corrosion-resistant equipment, and robust purification to remove residual acids/salts/-metal ions and oxidative debris [36]. Contamination is therefore an important issue. Broad surveys report metallic residues at the thousand-ppm level in a substantial fraction of commercial GO samples, with measurable impacts on dispersion pH, stability, film formation, and electronic properties. These impurities are particularly problematic for biomedical use because they can confound both performance (e.g. unintended redox/ionic effects) and safety (local irritation and oxidative stress). In biosensors that rely on biocatalytic functions, such random impurities (particularly metallic ones) can adversely affect the performance (sometimes even positively); however, this limits the applicability owing to low reproducibility.

Even when GO disperses well in water, its stability cannot be guaranteed over clinically relevant timescales or matrices. Commercial GO dispersions show large pH variability (≈4.4–8.6 at a fixed nominal concentration), consistent with differences in residual additives and synthesis protocols, and many products exhibit poor stability on storage or upon changing ionic conditions. Empirically, only a subset of commercial GOs maintain 'good' aqueous stability under simple conditions, and stability decreases with increased flake thickness and decreased O/C ratio; parameters that vary widely by supplier and lot. In biomedical settings, additional destabilizers (salts, proteins, lipids, shear, adsorption to containers, sterilization/cleaning) can further shift the aggregation state and surface chemistry, altering both function and biological response [37].

Another issue is that biocompatibility is conditional and not guaranteed and testing is technically demanding. The bioresponse of GO depends strongly on the *nanoform* and *biomolecular corona* formed *in situ* (which can modulate uptake, biodistribution, and toxicity). This creates two barriers: (i) safety cannot be inferred from 'GO' as a label, and (ii) routine bioassays can be limited by GO aggregation and assay interference. Regulatory-focused analyses highlight that aggregation can distort outcomes in standard genotoxicity endpoints and that adaptations (e.g. controlled agitation) may be required for GRMs to obtain reliable results [33]. A further, often underappreciated issue is endotoxin contamination and endotoxin assay interference, which can mislead immunotoxicity conclusions unless explicitly controlled with validated protocols.

While graphene standardization is advancing, the biomedical translation of GO still suffers from inconsistent reporting and incomplete material 'identity cards' (thickness/lateral size distributions, O/C ratio and functional group speciation, residues, dispersibility/aggregation kinetics, and stability in relevant media). International standards exist for terminology and structural characterization frameworks in the graphene family (e.g. ISO vocabulary and ISO structural characterization sequences); however, GO-specific adoption in biomedical pipelines remains uneven and is often not tied to the acceptance criteria for clinical endpoints. Complementary guides emphasize that for 'unknown' graphene-family materials (including GO), quantifying the thickness and lateral size distributions and measuring the oxidation level (C/O) are essential for quality control. However, as already highlighted, these

practices are still not universal across literature and supply chains. Critically, the absence of robust, standardized detection/quantification methods in complex matrices (e.g. body fluids and filtrates) also hampers the assessment of the exposure and release of GO-enabled biomedical products [33].

3.2.2. Technology evolution

By 2027, GO will be increasingly recognized as a family of nanoforms rather than as a single material, forcing a shift toward standardized classification and reporting, which will enable procurement-grade specifications and meaningful inter-study comparability. Comparative assessments of commercial GO show wide diversity in oxidation states, functional group populations, dimensions, and impurities, which can decouple results across analytical methods and laboratories [34, 35].

On the manufacturing side, the trajectory is toward greener oxidation/exfoliation and improved process controllability. Beyond incremental 'modified Hummers' refinements, electrochemical approaches are advancing because they can reduce the hazardous oxidant burden and enable finer control of oxidation conditions [38]. In parallel, industrial GO exfoliation is expected to increasingly rely on higher-yield, mature routes (e.g. thermal expansion) rather than ultrasonication-limited laboratory workflows.

For clinical-adjacent biosensing and diagnostics, by ∼2027, pilot-scale deployments are most plausible when GO is used as a non-implantable, well-contained reagent/component (e.g. optical cartridges, coated substrates, enclosed microfluidics), because containment reduces release concerns while still leveraging the chemistry and/or photophysics of GO.

By 2030, the field's maturation is likely to appear as GO-enabled subsystems rather than GO alone. For example, hybrid stacks in which GO provides a functional interface (biochemistry and optical/electrostatic control) coupled to robust transducers (electrochemical/photonic/electronic) and packaging designed for real matrices (biofluids) and real workflows (sterilization/cleaning, where relevant). Wearable and PoC (point of care) directions will be shaped heavily by integration engineering, such as flexible substrates, encapsulation, antifouling strategies, and data analytics, which is consistent with the broader graphene family of wearables [22].

A key enabler for regulated markets is the continuing alignment of GO/GRM testing with internationally recognized frameworks. The SafeGraph-derived regulatory analysis [33] highlights that, in the medical device sector, standards for nanomaterials within biocompatibility evaluation (e.g. ISO 10993-22) exist, but also identifies practical limitations and gaps for GRMs, including the need for standardized physicochemical characterization and for methods that remain 'under development' for GO/GRM behavior in complex environments. It is also emphasized that GRM aggregation/sedimentation and matrix complexity can compromise standard hazard/exposure tests, unless the protocols are adapted. This issue will strongly influence the types of GO products that can realistically gain approval.

3.2.3. Market & costs

GO is a smaller but fast-growing segment of the graphene market. The global graphene oxide market was valued at approximately USD 240–300 million in 2024 and is expected to grow at a CAGR of approximately 32% from 2025 to 2037, reaching approximately USD 8–10 billion by 2037 [39, 40]. This indicates that the GO industry is projected to grow to roughly USD 550–700 million by 2027 and up to 1.3 billion by 2030, depending on market uptake.

Currently, laboratory-grade GO can be purchased at approximately USD 100–500 kg^{-1} (depending on purity, dispersion form, supplier), whereas bulk GO powders on B2B platforms are 50% cheaper (∼USD 50–200 kg^{-1} for industrial-grade). These prices are expected to decline with greener, scalable syntheses and roll-to-roll production, with low-grade GO reaching as low as USD 30–100 kg^{-1} by 2027 and USD 20–50 kg^{-1} by 2030. Nevertheless, industrial-grade GO will remain high or even increase (>USD 500 kg^{-1}).

3.3. Reduced graphene oxide (rGO)

Reduced graphene oxide (rGO) is a chemically, thermally or laser-treated form of graphene oxide (GO) in which the majority of the oxygen-containing groups have been removed ('reduction'). The partial reduction of rGO restores portions of the conjugated carbon network (see GO) and therefore increases conductivity, but rGO generally remains structurally defective and chemically heterogeneous. Consequently, their functional group density and electrical properties vary widely according to the reduction protocol [27, 29]. Consistent with this, recent manufacturing-focused analyses emphasize that the reduction step is often the most critical determinant of rGO quality, with multiple competing reduction strategies (chemical, thermal, microwave, electrochemical, solvothermal) and different trade-offs in defects, waste handling, and scalability. Depending on the reaction mechanism, the rGO obtained using different reductants can exhibit significantly different electrical, chemical, and interfacial properties.

rGO sits 'in between' GO (highly oxidized, insulating, hydrophilic) and pristine graphene (nearly defect-free, highly conductive, hydrophobic). This balance makes it versatile for applications that

require both moderate conductivity and chemical compatibility.

rGO is widely used in energy storage electrodes, flexible electronics, composites for EMI shielding, (bio)sensors, and water purification systems. Thus, it is considered a more scalable and cost-effective graphene derivative. Particularly in biosensing, rGO is extensively used because of its improved electrical conductivity and the presence of residual oxygen-containing functional groups, which enable covalent or strong noncovalent coupling of bioreceptors and can enhance electron transfer and detection performance. This combination of conductivity and surface functionality makes rGO particularly suitable for electrochemical biosensors that require efficient electron transfer and robust bioreceptor immobilization.

3.3.1. Roadblocks/barriers

A central barrier for rGO translation in biomedical technologies is that 'rGO' is often not a uniquely defined material, but a continuum of nanoforms whose properties depend sensitively on precursor GO, reduction chemistry, and post-processing. Comparative characterization of commercially supplied 'graphene/GO/rGO' materials has shown substantial divergence between supplier claims and measured structure across length scales, underscoring persistent procurement risk and weak cross-laboratory reproducibility when rGO is specified only by a trade name or generic label [41].

Owing to its process-dependent structure and batch variability, the performance of rGO is highly sensitive to the reduction pathway and the extent of deoxygenation. Different reduction methods can yield markedly different residual functional groups and conductivities, directly affecting the interfacial behavior and device-to-device consistency [27]. Industrially, chemical reduction remains common because of process maturity; however, it generates waste streams, whose treatment cost and environmental burden are increasingly viewed as limiting factors at scale [7]. Thermal reduction can be operationally simple but may introduce or amplify lattice defects with knock-on effects on chemical reactivity, stability, and noise in electronic readouts. While microwave and electrochemical routes are advancing as potentially cleaner, faster, and more controllable alternatives, they still yield rGO, whose properties must be tightly benchmarked against biomedical performance requirements rather than assumed from nominal process descriptors. For rGO electrodes, the performance is often governed by mesoscale conductive network formation and not only by intrinsic sheet conductivity. Roadmapping from battery electrode science provides transferable guidance: agglomeration/restacking, inadequate mixing, and poorly engineered porosity can yield electronically 'dead' zones even when rGO is nominally conductive. For biomedical electrochemical sensing, this translates into a barrier of reproducible percolation and accessible surface area, requiring controlled dispersion protocols, binder/solvent selection, and microstructure-aware fabrication to avoid false gains (high apparent sensitivity in one batch and collapse in the next [36]).

Residual oxygen, defects, and drifting electronic properties are also included in the barriers. Even when conductivity is 'restored,' rGO electronic structure remains strongly influenced by residual oxygen content and defect density; reported effective bandgaps and electronic properties vary with reduction degree and oxygen population, reinforcing the need for rigorous specification beyond 'reduced' versus 'oxidized' labels [11, 29]. rGO produced via oxidation–reduction inherits impurity risks from both the GO precursor (e.g. metallic residues) and reduction/-workup steps (e.g. residual reducing agents, salts, and adsorbed organics). Such impurities can directly interfere with the electrochemical transduction and, in some cases, spuriously enhance or suppress biosensor signals, further undermining their reproducibility.

Laser reduction directly addresses these limitations, as ultrafast localized heating enables deep deoxygenation, defect annealing, and graphitic reordering, yielding rGO with high sp^2 content, low sheet resistance, and markedly improved uniformity. With digitally controlled fluence, pulse width, and ambient conditions, laser-reduced graphene can be patterned *in situ* on a target substrate to produce reproducible high-performance graphene-like conductors suitable for scalable manufacturing [11].

Large surveys of GO quality have emphasized that structural details and impurities (including metallic contaminants) are frequently under-reported and can be substantial, with these issues propagating into derivative materials, unless explicitly controlled [34, 35]. Its biological response depends on nanoform and surface chemistry. Safety- and performance-relevant biological interactions are not intrinsic constants for rGO, as they depend on lateral size/thickness, surface chemistry, carbon-to-oxygen ratio, and the number of layers, among other parameters [8]. This creates a translational bottleneck: 'positive' biocompatibility results for one rGO nanoform cannot be generalized across other rGO materials with different oxidation/reduction histories or dispersibility. Therefore, robust translation requires harmonized nanoform descriptors that are tied to biological endpoints and exposure scenarios.

Regulatory qualifications and test method artifacts should also be considered. For medical devices containing (or generating) nano-objects, ISO/TR 10993-22 provides guidance for biological evaluation, including consideration of nano-objects released by degradation, wear, or mechanical processing. In practice, GRMs pose methodological challenges because

aggregation and sedimentation can undermine standard toxicology and genotoxicity assays, which require protocol adaptations (e.g. agitation and modified dosimetry approaches) to obtain interpretable results [33]. To hazard testing, another barrier is the limited availability of standardized methods for the detection and quantification of GRMs in complex matrices relevant to exposure and release assessment, which is increasingly important for regulated biomedical products.

3.3.2. Technology evolution

Similar to GO, rGO is expected to have a wider adoption by 2027 owing to its more efficient and green reduction (ascorbic/biobased) and hydro/solvothermal routes with fewer defects [42]. This will be further enhanced by improved terminology via ISO/TS 80004-13:2024 and uptake of ISO/TR 19733/ISO 21356-1 for characterization workflows. Simultaneously, hybrid inks based on rGO will evolve, achieving lower resistance and retaining high transparency. This would result in flexible, sensitive, and wearable biosensors that are both high performance and manufacturable at scale.

rGO will also increasingly move from a loosely defined 'conductive GO derivative' toward an engineered, specification-driven material class, in which the degree of reduction (residual O content), defect density, flake size/thickness distribution, and impurity profile are deliberately tuned to match the functional role (e.g. flexible conductors, interconnects, coatings, and biointerfaces). Because the oxygen content and reduction severity directly modulate the electronic structure and conductivity, the next development cycle emphasizes the quantitative control of reduction chemistry/physics rather than maximal deoxygenation, enabling application-specific tradeoffs between conductivity, wettability, colloidal/ink stability, and process compatibility (e.g. via thermal annealing windows, electrochemical potentials, or photothermal dose and specific laser wavelengths corresponding to targeted bond vibrational energies).

The production process will intensify, become greener, and follow scalable reduction methods. Although chemical reduction remains widely used in industrial production owing to process maturity, its long-term scalability is increasingly constrained by the environmental and economic burden of treating reduction-derived liquid waste streams, accelerating the shift toward dry/solvent-free processes and electrically driven approaches. In this near-term horizon, the most impactful advances are expected from (i) microwave reduction, which combines rapid volumetric heating with high-throughput potential and is repeatedly highlighted as promising for large-scale manufacturing while preserving structural integrity better than harsher thermal routes; and (ii) electrochemical reduction, which supports reagent-minimized workflows and can be integrated directly with device substrates or electrode architectures. Complementary 'green reductant' chemistries (e.g. benign organic reductants) will continue to expand in situations where aqueous processability and low-toxicity residues are paramount. However, industrial adoption will likely hinge on reproducibility, residual impurity control, and validated downstream purification.

From 2027 to 2030, we should expect the development of on-substrate conversion, patterning, and printing-ready rGO. A strong trajectory is the migration from batch synthesis toward spatially resolved on-substrate conversion of GO to rGO, enabling device integration without transferring fragile films or exposing materials to additional contamination steps. Laser/photothermal reduction is particularly attractive because it is chemically free, fast, and digitally patterned on flexible substrates. For example, photothermal laser conversion of GO to rGO under ambient conditions has demonstrated low sheet resistance on selected flexible membranes, underscoring the potential for scalable roll-compatible patterning once dose–substrate interactions are standardized (laser wavelength/pulse conditions, thermal boundary conditions, and substrate roughness/porosity [43]). In parallel, technologies following printing and then reducing the step sequences can lead to improved ink engineering. Recent work has demonstrated screen-printable rGO-based inks using more sustainable binder/solvent systems, supporting low-voltage printed device integration and highlighting the broader transition to manufacturing-relevant rGO formulations [44]. Together, these trends are likely to mature rGO into a platform material for scalable, flexible electronics and bioelectronic components, where performance depends as much on rheology, adhesion, curing/annealing compatibility, and encapsulation as on intrinsic conductivity.

Metrology, standards, and biomedical translations are expected to be the primary accelerators of the rGO roadmaps. Over the next 3–5 years, the most commercially meaningful progress will come from coupling scalable production with standardized terminology and measurement workflows, so that rGO procurement converges with reproducible device performance. ISO standardization efforts for graphene and related 2DM (ISO/TS 80004-13) and ISO guidance on the structural characterization of graphene materials from powders/dispersions (ISO/TS 21356-1) provide a foundation for harmonized descriptors (layer number/thickness, lateral size, disorder, and surface area) and comparability across suppliers and laboratories. Similarly, the ISO property–measurement matrix (ISO/TR 19733) helps translate application requirements into testable acceptance criteria. These standards enable 'quality-by-design' supply chains in which rGO lots are

qualified against fit-for-purpose specifications (e.g. Raman metrics, XPS-derived O/C, conductivity targets, metal residues by ICP-MS, and dispersion stability) rather than generic or incomplete labels.

Technological evolution in biomedical products is driven by regulatory-grade evidence packages. Guidelines for nanomaterials in medical devices emphasize nanomaterial characterization, sample preparation, nano-contaminant release, and risk assessment (ISO/TR 10993-22). Recent analyses of GRMs highlight practical needs such as quantifying potential release into relevant body fluids and adapting testing workflows when aggregation/sedimentation interferes with conventional assays. Simultaneously, sterilization/cleaning compatibility has become a concrete engineering target. For graphene coatings on implant-relevant substrates, systematic studies have indicated that certain standard sterilization routes can preserve the coating integrity and function, providing a methodological template for qualifying related graphene-family coatings intended for clinical environments [45].

3.3.3. Market & costs

The global rGO market is estimated to be USD 500 million by 2024 [46] and is projected to reach USD 1.5 billion by 2033, reflecting a 15.5% increase in CAGR. This increase is linked to the fact that rGO offers improved conductivity and strength compared to GO while maintaining cost efficiency. A potential hurdle in the popularity of rGO is its ambiguous standardization, which hinders its industrial scaling and development.

In terms of costs, rGO is currently available around USD 50–200 g^{-1} depending on the quality and grade of rGO. For biosensing specifically, an indicative cost has been identified at €0.5–1 per sensing unit for laser-scribed rGO electrodes, which is expected to drop to €0.2–0.4 by 2027 and less than €0.1 per unit for mass-fabricated graphene biosensing elements.

3.4. MXenes

MXenes are a family of 2D materials composed of transition metal carbides, nitrides, and carbonitrides, with the general formula $M_{n-1}X_nT_x$, where M is a transition metal, X is carbon and/or nitrogen, and T represents surface terminations, such as–OH,–O, or–F. These materials are produced by selectively etching the A-layer from MAX phases, resulting in nanosheets with a high surface area, metallic-like electrical conductivity, and tunable surface chemistry, which make them prime candidates for biosensing [47, 48].

The exceptional conductivity of MXenes reduces the resistance between the biorecognition layer and the electrode, accelerating electron transfer directly from the active sites to the electrode, and amplifying signals without mediators [50]. Their ultrathin 2D structure shortens the diffusion paths, enhances the response times, and lowers the detection limits. Mechanical stability, inherent hydrophilicity, and versatile optical properties further bolster these advantages, enabling sensitive, selective, flexible, and biocompatible sensors for analytes, such as disease biomarkers, pathogens, and environmental pollutants [51, 52].

Compared to graphene, MXenes offer conductivities over two orders of magnitude higher. While graphene also requires functionalization for hydrophilicity, MXenes achieve this intrinsically through manufacturing-induced surface terminations (–OH, –O, –F). MXene-based electrochemical biosensors have demonstrated exceptional potential for detecting clinically relevant biomarkers such as proteins [53], RNA [54], small molecules [55], and pathogens [56]. Their ability to achieve ultra-low detection limits (LoDs) [57] and high signal stability has positioned them as key players in addressing the challenges of early disease detection and therapeutic monitoring.

3.4.1. Roadblocks/barriers

Challenges in utilizing MXenes for biosensing include the oxidative instability common to biosensors under physiological conditions and difficulties in real-world applications. MXenes are prone to oxidation in aqueous and ambient environments, leading to deterioration of electrical conductivity, 2D morphology, and structural integrity [58, 59]. Achieving consistent quality and morphology during large-scale synthesis remains difficult owing to variations in etching conditions and precursor purity [60].

Currently, hydrogen fluoride (HF)-based etching methods (direct or *in situ* HF) are the dominant approaches for synthesizing MXenes; however, these methods are hazardous [61]. These issues limit the transition from laboratory prototypes to practical devices. Reproducible, scalable, and eco-friendly synthesis methods are required to ensure consistent quality and biocompatibility.

Comprehensive studies are also required to meet regulatory standards for medical applications. *In vitro* and *in vivo* studies are required to confirm the long-term biocompatibility for medical applications, which is time-consuming and costly. Furthermore, incorporating MXenes into flexible substrates or microfluidic platforms without compromising performance is still under development, and meeting stringent regulatory standards for clinical diagnostics adds complexity and delays commercialization.

3.4.2. Technology evolution

By 2027, ongoing scientific efforts to prevent the oxidation of MXenes via surface coating, passivation, and hybrid composite engineering will lead to the development of more stable and biocompatible materials [58, 62]. Approaches such as polymer encapsulation, antioxidant additives, cation intercalation

and MXene–graphene heterostructures are anticipated to substantially extend the operational lifetime of MXenes in physiological and ambient environments. Simultaneously, improvements in scalable and reproducible manufacturing through continuous-flow synthesis, molten salt etching, and fluorine-free etching protocols will enhance batch consistency and facilitate the standardization of MXene libraries with controlled surface terminations. At the same time, more established environmentally friendly (HF-free) synthesis approaches [63] are expected to further improve the overall process.

The development of oxidation-free MXene-based inks is expected to increase the availability of printed biosensors for diagnostic applications by 2030. The integration of MXene-based biosensors into wearable and implantable devices is expected to be empowered by advances in printable MXene inks, flexible electronics, and microfabrication techniques. These systems enable continuous health monitoring and early detection of disease [64]. Additionally, improvements in multiplexed detection capabilities will allow for simultaneous analysis of multiple biomarkers, thus providing comprehensive diagnostic outputs from a single sensing platform [52].

Additive manufacturing (AM) significantly reduces biosensor prototyping costs by using inexpensive filaments, such as PLA-carbon composites, enabling rapid on-demand production in minutes versus days for traditional methods, although economies of scale remain limited by post-processing needs and low-volume efficiency compared to injection molding for mass production. AM with MXene composites addresses miniaturization, whereas stability improvements via polymer coatings mitigate oxidation in implantable applications [65, 66].

By 2030, MXene-based biosensors are expected to be fully integrated into personalized healthcare systems, serving as core components in real-time diagnostics and monitoring [67]. Advancements in nanotechnology and materials science will enable the development of highly sensitive and selective sensors capable of detecting a wide range of analytes at low concentrations [68].

Such improvements will strengthen the performance of the electrochemical, optical, and multimodal sensing modalities. Furthermore, the incorporation of AI and ML (machine learning) algorithms enhances data analysis and interpretation, leading to more accurate and timely medical decisions. Additionally, such sensors will have a competitive pricing compared to government health bills, reducing diagnostic waiting time and freeing resources for life-threatening cases.

3.4.3. Market & costs

Recent reports indicate that the global MXene market is valued at approximately $26–30 million and is expected to grow at a CAGR of roughly 29%, reaching a value nearing $121 million by 2027 [69]. This growth is driven by the increasing demand for advanced biosensing technologies in healthcare and environmental monitoring applications. Currently, the price of MXene is approximately USD 400–500 per 250 mg.

By 2027, the market for MXene-based biosensors is expected to expand significantly with applications in medical diagnostics, environmental monitoring, and wearable health devices. The integration of MXene-based sensors into PoC diagnostics and personalized medicine is expected to drive the market growth. As production scales and synthesis processes improve, unit costs per gram may decline significantly; however, prices in actual commercial supply will likely remain elevated through the mid-2020s, because industrial-scale MXene production is still emerging.

By 2030, MXene-based biosensors are projected to be integral components of smart healthcare systems, offering real-time, non-invasive diagnostics and monitoring. The widespread adoption of these technologies is expected to improve patient outcomes and reduce healthcare costs through early detection and personalized treatment strategies.

3.5. Aptamers

Aptamers are short, single-stranded DNA or RNA sequences that can form unique 3D structures, such as proteins. Primarily designed to mimic antibodies, these 'chemical antibodies' offer an alternative recognition element with comparable affinities, are less expensive, have smaller molecular sizes, and are more biocompatible [70]. The aptamers have added advantages over antibodies, such as batch-to-batch reproducibility and permanent sourcing owing to chemical synthesis, and can also be generated against targets that are toxic in nature. Aptamers also have excellent specificity, allowing them to distinguish between different isoforms of a target (e.g. protein) while being more stable under harsh conditions.

These advantages render aptamers ideal for targeting a range of analytes, rendering them a potent rival of antibodies for therapeutics and biosensing. Their remarkable binding affinities, combined with their facile synthesis and easy modifications, have led to their extended use in various nanomaterials such as nanoparticles and graphene-based substrates. This has enabled the development of novel biosensors (i.e. aptasensors) with improved performances and wider commercial applications. Such biosensing devices hold immense value as low-cost solutions, particularly for PoC *in vitro* detection (PoC IVD) systems. Typical aptamers are ∼12–80 nucleotides long and can selectively bind not only proteins, but also small molecules, carbohydrates, and whole cells, broadening their applicability beyond classical antibody targets.

Aptamers were identified in randomly synthesized oligonucleotide libraries of huge diversity through an *in vitro* experimental approach first described in the 90 s and named systematic evolution of ligands by exponential enrichment (SELEX) [71, 72]. This involves iterative cycles of oligonucleotide pools binding to the target, followed by separation of the complexes formed, amplification of the bound oligonucleotides, and their reintroduction into the next selection cycle. With each selection cycle, the selection parameters are made more stringent, and this process progressively enriches the population into molecules with a high affinity for the intended target. Typical SELEX libraries start from $\sim 10^{15}$ random sequences, and after 5–15 rounds of selection and counter-selection, enriched pools are sequenced and analyzed bioinformatically to identify high-affinity candidates.

Ultimately, this makes it possible to isolate aptamers that can recognize cognate target molecules with high specificity and affinity, including proteins, thus making them ideal probes or recognition elements for sensors, pathway inhibitors, and diagnostic applications. Today, there are multiple versions of this approach depending on the target/library, separation of complexes, and the experimental setup. More than 30 SELEX variants have been developed, enabling selection strategies tailored to different targets, matrices, and binding mechanisms (e.g. cell-SELEX, capillary electrophoresis-SELEX, and structure-switching SELEX) [73].

In addition to antibodies, other techniques can be used to detect and measure certain biomarkers (e.g. detection of $A\beta_{1\text{-}42}$ by positron emission tomography (PET)); however, these have increased costs.

3.5.1. Roadblocks/barriers

No aptamers have been reported for any of the biomarkers. This has led to the need to identify new ones. However, limited knowledge about structure-function relationship limits the rational design, hence prompting new selections processes, which require substantial resources and is currently based on a 'try-and-error' approach. In addition, several reported aptamers have low sensitivities or do not work under the desired detection conditions; hence, optimization and selection of new aptamers are required to obtain new probes. This creates a bottleneck for rapid translation, particularly when new biomarkers emerge or when aptamers must be reselected to function in complex clinical matrices.

At present, aptamer discovery platforms are limited to working on a limited number of parallel selections, which is expected to become a significant constraint as the demand for multiplexed biomarker panels and personalized diagnostics increases. Scaling aptamer discovery to high-throughput parallelized formats remains a key technical and infrastructural challenge.

3.5.2. Technology evolution

For *in vitro* selection, DNA and RNA aptamers will benefit from the introduction of non-canonical bases to increase their binding affinities by 2027. New innovations in chemically modified DNA/RNA backbones will lead to increased nuclease resistance. Diversity can be further enhanced by optimizing PCR amplification and engineering new polymerases [74] that can tolerate a wide range of modifications [75]. The detection limits and specificity of aptamers are expected to increase with technologies such as multivalent aptamers [76]. Structure-switching [77] and multivalent aptamer [78] designs are expected to play an increasing role in next-generation biosensors, enabling intrinsic signal transduction and an improved signal-to-noise ratio without the need for complex labeling strategies.

The aptamer selection process is expected to be significantly supported by AI and automation. Current AI prediction models show promising outcomes, although they struggle with small datasets to work upon. These models are expected to improve as larger datasets of aptamer sequences, structures, and binding behaviors become available. Coupling automated SELEX with AI is anticipated to accelerate hit identification, reduce the number of experimental cycles, and enable partial *in silico* prescreening of candidate sequences.

By 2030, the number of aptamer-based kits/delivery vehicles/therapeutics will increase, making their way into diagnostics and therapeutics, whereas several aptamer-based therapies in clinical trials will have produced results. Notably, the regulatory approval of aptamer drugs (i.e. pegaptanib [79]) has established a clinical precedent, supporting confidence in aptamer-based modalities for regulated diagnostic and therapeutic applications. Along with the role of AI in the prediction and discovery of new aptamer ligands, automation will make the selection process time efficient and less resource intensive.

3.5.3. Market & costs

The global aptamers market size was estimated at USD 2.91 billion in 2024 and is anticipated to reach around USD 5.62 billion by 2027 and USD 10.88 billion by 2030, growing at a solid CAGR of 24.59% [80]. This growth is primarily fueled by diagnostic innovations, with aptamers surpassing traditional antibody technologies because of their greater stability, lower production costs, and ease of modification. The rise of wearable biosensors and their integration with nanomaterials (e.g. graphene, MXenes, and gold nanoparticles) is a major enabler, showcasing strong collaboration in the domain.

Projections toward 2030 place aptamers as a mainstream technology for biosensing applications, such as PoC diagnostics, personalized medicine, and multiplexed environmental sensors. The replacement of antibodies in selected niches, coupled with the

expansion of nanomaterial-aptamer hybrids, will drive sustained growth.

The rapid expansion of the aptamer market is partially attributed to the fact that synthetic DNA/RNA aptamers cost less than monoclonal antibodies, with custom synthesis typically ranging from USD 100–500 per milligram, depending on the sequence length, modifications, and purity. For research-grade use in biosensing assays, aptamers can be ordered from oligonucleotide synthesis companies at costs comparable to those of the primers or probes. However, functionalized aptamers (e.g. those with fluorophores, thiols, or biotin tags) incur additional costs.

By 2027, costs are expected to decline due to the scaling of automated high-throughput oligonucleotide synthesis and improved selection platforms (including SELEX automation and AI-based *in silico* design). Unit costs for standard aptamers could fall by 20%–30% [81], making large-scale deployment in disposable biosensors economically feasible.

By 2030, aptamer costs for biosensing are likely to approach commodity levels, with functionalized sequences available at <USD 100 per milligram for most standard modifications. This enables further integration into roll-to-roll manufactured diagnostic strips, wearable patches, and IoT-linked devices.

3.6. MNPs

Nanoscale materials have unique properties that distinguish them from regular materials, which makes them ideal for several biomedical applications. Out of a large pool of nanomaterials, MNPs are one of the most widely researched and applied nanomaterials in life sciences.

MNPs possess a set of distinctive properties that make them essential for a wide range of applications. These properties include high surface-to-volume ratio, superparamagnetic behavior, excellent biocompatibility, low toxicity, and the ability to enable site-specific targeting. In addition, their cost-effective and sustainable production further enhances their suitability for diverse biomedical applications [82].

When combined with biosensors or aptasensors, MNPs can enhance overall biosensing sensitivity, specificity, and reliability [83]. MNPs help sample purification and prevent nonspecific signals. They also play a crucial role in controlling the flow at different stages of the bioassay, for example, incubation of bioreceptors with the sample, purification, recognition, and signal acquisition.

Surface functionalization of MNPs enables selective binding to DNA, proteins, or cells, while their magnetic properties enhance detection signals. MNPs can also function as magnetic separators, allowing efficient isolation of target biomolecules from complex mixtures through flow control. This capability further supports advanced multiplexing by enabling the simultaneous targeting of multiple analytes. Additionally, certain MNPs, such as Fe_3O_4, exhibit enzyme-like activity that contributes to biosignal generation.

3.6.1. Roadblocks/barriers

The key barriers for MNPs in biosensors are (i) reproducible, monodisperse synthesis, and stable surface functionalization to avoid aggregation and loss of activity; (ii) matrix effects and nonspecific binding in complex clinical or food samples that reduce specificity; (iii) reader standardization and integration into robust and standardized sensing platforms (many magnetic detection methods require dedicated low-cost magnetometers for fieldwork); (iv) high-purity MNPs and integrated systems that are expensive; and (v) regulatory and clinical validation pathways for any new *in vitro* diagnostics using nanoparticle reagents.

3.6.2. Technology evolution

By 2027, MNP-enabled biosensing is expected to widen the deployment of magnetic enrichment front-ends for LFA and microfluidic PoC workflows, improve magnetic tags (such as doped ferrites and core shells) that provide stronger, more stable signals, and mature compact magnetic readers (GMR/TMR and DC magnetometers) that enable quantitative, smartphone-compatible readout. These advances have been driven by published demonstrations of magnetic tagging in LFAs and magnetic signal differentiation methods [84].

In 2030, technical trends point to integrated PoC cartridges, where standardized, functionalized MNPs are central to sensitivity, selectivity, and real-world deployment by performing capture/enrichment, providing quantitative output. The expanded use of multiplexed magnetic barcoding enables the simultaneous detection of multiple targets, whereas advances in biocompatible surface coatings have minimized nonspecific binding. Together, these developments are helping in the transition of magnetic assay technologies from specialized laboratory environments to routine clinical diagnostics and field-deployable applications [85].

3.6.3. Market & costs

The market for MNPs (broadly defined) was a niche, but a growing segment in 2025. With an estimated market size of USD 6.0 billion, the MNP market is expected to reach an estimated $7.8 billion by 2030 with a CAGR of 4.6% (∼USD 6.86 billion by 2027) [86]. The major drivers of this market are the rapid expansion of the nanotechnology sector and the growing demand from the biomedical, electronics, and wastewater treatment industries.

In the current market, the cost for MNPs depends on several factors, such as size, coating (e.g. streptavidin, antibodies), and magnetic core (e.g. Fe_3O_4, $CoFe_2O_4$), ranging from USD 200–1000 g^{-1}. This cost

is expected to decrease significantly within the next two years (<USD 200 g^{-1} by 2027) through large-scale synthesis and simplified surface modifications. By 2030, with established manufacturing lines, bulk MNP powders and common functionalized beads are likely to be available at substantially lower unit costs (<USD 50–100 g^{-1}) while advanced bespoke tags and regulated clinical-grade batches will still command higher prices due to QA/GMP overhead and certification costs. Continued downward pressure on prices will be driven by wider biosensor adoption and optimized roll-out of magnetic reader platforms.

Table 2 presents an overview of the materials' innovation sphere, summarizing key benefits, roadblocks/barriers, technology evolution, and market and cost trends for each material.

4. Components

4.1. Electrodes for lateral flow electrochemical biosensors

Lateral flow simplicity is combined with electrochemical quantification. Electrochemical biosensors convert biochemical signals into electrical signals (current, potential, conductance, or impedance) via redox reactions. The signal was measured using a transducer, providing quantitative results. This is achieved by printing or depositing graphene electrodes that transduce biochemical binding events into electrochemical signals.

It is portable, low-cost, and rapid (typically <15 min). It enables quantitative, sensitive, and multiplexed detection, and is compatible with PoC diagnostics. It operates with small sample volumes (5–50 μl) and can use various bioreceptors (antibodies, aptamers, and enzymes).

Core materials include graphene derivatives (rGO, few-layer graphene, graphene ink/paste, and graphene quantum dots) used in electrode inks or films, substrate materials (PET, paper, nitrocellulose membranes, and pads for sample/conjugate/wicking), biorecognition elements (antibodies, aptamers, enzymes, and DNA probes), labels/mediators (Prussian Blue, gold nanoparticles, enzymes, and redox mediators), conductive adhesives and encapsulants, and standard LFA reagents (blocking proteins and buffers). The choice of the graphene form and ink formulation is critical for conductivity, stability, and biocompatibility [87]. Laser-based graphene electrodes, after proper functionalization, have been systematically explored as electrochemical sensors and biosensors for targets ranging from gases and heavy metals to biomolecules and pathogens, revealing their vast potential. However, several challenges remain unaddressed [88, 89]. Recent advances in laser-assisted printstamp and laser-induced reduction technologies have enabled the *in situ* conversion of GO to highly conductive rGO directly on device substrates in a solvent-free, single-step process. These digitally patterned approaches support scalable manufacturing, reduce contamination and transfer steps, and enable the direct integration of rGO electrodes into nitrocellulose membranes for electrochemical lateral flow assays while preserving the fluidic performance.

Recent research has also introduced the concept of high-performance electrochemical sensors using MXene/graphene hybrids as the sensing materials. This hybrid material is expected to provide high sensitivity, selectivity, stability, reproducibility, low LoD, and high electroactive area.

4.1.1. Roadblocks/barriers

Major barriers include scaling reproducible graphene inks and integration methods for roll-to-roll high-volume manufacturing, ensuring long-term storage stability of bioreceptors on electrochemical strips, minimizing batch-to-batch sensor variability, achieving a high signal-to-noise ratio in complex matrices, navigating regulatory pathways for combined nanomaterial-enabled medical devices, and meeting the requirements for standardized, inexpensive, and robust reader electronics and data protocols.

Translating lab sensitivity into rugged, user-friendly devices that survive supply chain and environmental stresses remains nontrivial. While laser-based on-substrate graphene patterning reduces transfer-related variability, standardization of laser dose, substrate interactions, and post-patterning functionalization remains a barrier to cross-platform reproducibility and regulatory qualification.

Finally, biosensors using electrochemical transducers containing MXene have not been studied. The stability of inks containing MXene has not been previously evaluated.

4.1.2. Technology evolution

By 2027, there will be a wider adoption of printed graphene electrodes (screen/inkjet/aerosol-jet) integrated into hybrid LFA formats, more commercial demonstrations of enzyme/mediator-based electrochemical strips for clinical analytes, and modest cost reductions owing to improved ink formulations and partial roll-to-roll pilot lines. The sensitivity is expected to be enhanced by integrating nanomaterials, whereas the LoD will reach lower levels, allowing a wider range of applications. This is also supported by multi-analyte approaches that allow for simultaneous detection of 3–5 analytes per strip.

The regulatory focus on nanomaterial safety and standardization of printed electrode QC will intensify, and compact potentiostat/reader modules with smartphone wireless connectivity (Bluetooth/5G/NFC) readers will converge to enable broader deployment in clinics and industries. These near-term trends are already visible in recent literature and printing demonstrations.

Table 2. Overview of the materials' innovation sphere.

Material	Key benefits	Roadblocks/barriers	Technology evolution	Market & cost evolution
Graphene (pristine & GRMs)	Ultrasensitive transduction, flexible electrodes, and FET biosensors. Large surface area supports high-density functionalization.	Scale–quality trade-off. Transfer contamination. Wafer-scale non-uniformity. Batch variability across GRMs. Stability concerns. Biocompatibility depends on nanoform. Limited regulatory precedent	Roll-to-roll production (↓ cost ∼50%). Transfer-free/laser direct-write approaches. AI-driven defect control & process optimization. ISO standard adoption for QC. Integration into wearables & bioelectronics. aM detection limits & multiplexing by 2030	∼$1.6B (2030), ∼35% CAGR. ∼€10 g^{-1} (2030), ∼90% reduction
Graphene oxide (GO)	Excellent dispersibility, surface chemistry, and bioconjugation capability. Ideal for coatings, drug delivery, and biointerfaces rather than conductivity-driven devices.	Low conductivity. Irreversible lattice defects. High batch variability. Metallic contamination. Instability in physiological media. Assay interference & endotoxins. Weak standardization in biomedical use	Shift to nanoform classification. Greener synthesis. Industrial-scale exfoliation. Use in contained systems (microfluidics). Hybrid systems (GO + transducers). Alignment with regulatory frameworks	∼$1.3B (2030), ∼32% CAGR. ∼$20–50 kg^{-1} (2030), ∼90% reduction
Reduced graphene oxide (rGO)	Enables efficient electron transfer while retaining functional groups for biomolecule attachment—ideal for electrochemical biosensors.	Poor material definition. Residual defects & oxygen variability. Impurity inheritance. Percolation/network instability. Chemical reduction waste. Limited standardization	Greener reduction. Laser/photothermal reduction. Printable inks for flexible electronics. Specification-driven production. Integration into scalable bioelectronic systems.	∼$1.5B (2033), ∼16% CAGR. Cost: €0.1/unit (2030), ∼80% reduction.
MXenes	Enable ultrafast electron transfer, low detection limits, and high signal amplification without extensive functionalization.	Oxidation instability. HF-based synthesis hazards. Limited scalability & reproducibility. Integration challenges. Limited long-term biocompatibility data. Regulatory complexity	Oxidation mitigation. HF-free synthesis. Continuous-flow scalable production. Printable inks for wearables & PoC. AI-integrated diagnostics. Multiplexed sensing & personalized healthcare	∼$121 M (2027), ∼29% CAGR. ∼$400–500/250 mg.
Aptamers	Offer high specificity, low cost, stability, and tunability, ideal as recognition elements in biosensors and nanomaterial hybrids.	Limited availability for many biomarkers. SELEX is slow & resource-intensive. Weak structure–function predictability. Sensitivity issues in complex matrices. Limited parallel discovery scalability	AI-assisted SELEX & automation. Modified nucleotides (↑ affinity, stability). Multivalent & structure-switching aptamers. High-throughput discovery platforms. Expansion into diagnostics & therapeutics	∼$10.9B (2030), ∼24.6% CAGR. Cost: <$100 mg^{-1} by 2030, ∼30% reduction
Magnetic nanoparticles (MNPs)	Enables target capture, enrichment, and signal amplification. Critical for sample preparation, multiplexing, and improving biosensor reliability in complex matrices.	Aggregation & poor monodispersity. Non-specific binding. Need for magnetic readers. High cost for functionalized particles. Regulatory barriers	Magnetic enrichment in PoC workflows. Advanced tags. Compact readers. Multiplexed magnetic barcoding. Integrated PoC cartridges by 2030	∼$7.8 B (2030), ∼4.6% CAGR. <$50–100 g^{-1} (2030), ∼70% reduction

By 2030, mass-manufacturing processes for graphene inks and printed electrochemical strips are likely to be mature enough for meaningful penetration into LFA market niches that require quantitation (e.g. chronic disease biomarkers, environmental monitoring, and some infectious disease assays).

Broader scaling of the graphene supply chain and improved material consistency will reduce the performance variability and enable broader multiplexed electrochemical LFA panels (>10 analytes per strip). Simultaneously, streamlined greener production processes allow for fully disposable or recyclable electrochemical LFA cartridges.

Integrated, low-cost readers and cloud analytics support distributed testing (including potential self-testing) by considering fully automated sample processing within the strip (e.g. plasma separation). Finally, regulatory acceptance is clear in several applications.

4.1.3. Market & costs

The lateral flow assay market is estimated at USD 10,9 billion in 2025 and it is estimated to reach valuation of USD 12 billion by 2027 and USD 13,9 billion by 2030 with a GAGD of 5% [90]. On the other hand, the global electrochemical sensors market size is estimated at USD 12.2 billion in 2025 and is projected to reach USD 18.4 billion by 2030, growing at a CAGR of 8.5% from 2024 to 2030. This steady progress is expected to evolve further if graphene-based electrochemical diagnostics are as accurate as the current lab-based diagnostics. In this market landscape, the cost of electrochemical biosensors is expected to increase.

Currently, the production cost per disposable printed electrochemical sensor in academic and early stage commercial reports ranges from less than USD 0.30 per unit to several USD per unit, including functionalization, packaging, and small-volume runs. For graphene-based printed electrodes, unit costs in low-volume production are typically between EUR 1.5 and 4.0 (with MXenes, the cost is higher, reaching EUR 5.0).

With modest scale-up, improved graphene ink formulations, and roll-to-roll printing, per-unit manufacturing costs for graphene-printed electrodes and strips could decline by 20%–40% relative to 2025 lab/-commercial pilot costs. With that in mind, by 2027, the cost can range from EUR 1.2–3.5.

By 2030, if graphene production scales and standardization reduce yield losses, a further 30%–50% decline versus 2025 pilot costs is plausible for high-volume production, putting material/manufacturing costs for disposables into EUR 0.5–3.0.

4.2. Graphene channels for FETs

Graphene-based FETs (GFETs) are transistor devices that use a graphene channel. The conductivity of the graphene channel is modulated by an external gate electrode; when functionalized with bioreceptors (antibodies, aptamers, nucleic-acid probes), the gate-induced changes caused by target binding produce a measurable electrical signal, enabling label-free, real-time biochemical sensing with high sensitivity and fast response [91].

In biosensing applications, GFETs capture (via appropriate biorecognition units/probes) target analytes at the graphene surface and transduce them to changes in drain-source current or Dirac point voltage. Typical functions include selective molecular recognition, rapid quantitative (or semiquantitative) readout, multiplex sensing by arrays, operation in liquid/physiological media for PoC, and wearable monitoring [92].

The devices consisted of graphene materials (CVD monolayer graphene, few-layer graphene, rGO, or liquid-phase-exfoliated graphene/graphene inks), dielectric/gate materials (SiO_2, high-k polymers, ion gels, or liquid gates for biological operation), metal contacts (Au, Ti/Au, Pt), substrate materials (Si/SiO_2, flexible PET/PI, paper, or microneedle platforms), and biochemical reagents for surface functionalization (linker chemistry, antibodies, aptamers, enzymes, blocking agents, and redox reporters when used). The choice of the graphene form determines the mobility, noise, and functionalization routes.

4.2.1. Roadblocks/barriers

The key barriers for GFETs are (i) reproducible, low-defect large-area graphene manufacturing and transfer (yield and variability) [93], (ii) device noise and baseline drift in complex biofluids [94], (iii) stable long-term functionalization and storage of bioreceptors [95], (iv) integration with low-cost readout electronics [96], (v) packaging for real environments, and (vi) regulatory/clinical validation pathways for regulated diagnostics [97]; these challenges slow translation from lab prototypes to high-volume commercial products, even though commercial products are already available (e.g. for COVID-19).

4.2.2. Technology evolution

By 2027, incremental but practical advances are expected: broader use of liquid-gated and top-gated GFET formats optimized for biofluids [96], improved printable graphene inks and hybrid patterning (spray/print + photolithography) for pilot manufacturing, emergence of short pilot production lines and research-grade commercial GFET modules for developers, and tighter best practices for surface chemistry and noise reduction [98]. This will enable the development of more demo devices in clinical studies and specialized industrial sensing.

By 2030, the maturation of graphene supply chains and standardization of printing/fabrication are likely to sufficiently reduce device variability and

cost for GFETs to enter selected commercial niches (wearables, continuous biomarker monitoring, environmental sensors, and some rapid diagnostics). At that point, integration with low-cost electronics, edge/cloud analytics, and multiplex GFET arrays can deliver validated and regulated products in high-value applications, provided that the clinical performance and long-term stability are demonstrated.

4.2.3. Market & costs

Graphene FET Chips Market is an emerging segment within the semiconductor industry, driven by the unique properties of graphene. The global GFET market is projected to reach USD 1.4 billion by 2025, indicating significant growth potential for GFET-based technologies [99]. With a CAGR of 18.5%, the market is expected to grow at USD 2.0 billion by 2027 and exceed USD 3.3 billion by 2030. By that time (2030), GFETs could capture meaningful revenue in targeted verticals (continuous monitoring wearables, industrial sensors, select clinical assays) provided reliability and regulation hurdles are resolved.

Research-grade GFET modules and bench sensors are sold at research prices (commercial sensor modules and single GFET chips are commonly priced in the USD 100s for small orders—vendor catalog examples list sensing GFET test chips from approximately USD 155 each), whereas prototype/low-volume device fabrication yields per-unit material costs that vary widely depending on the graphene type, processing, and assembly.

Manufacturing cost per GFET (materials + patterning + basic packaging) is expected to decrease significantly by 2027 compared to research-scale pricing; developers and early producers can plausibly lower per-unit production costs into a range that supports mid-volume commercial products, but reader/electronics and regulatory compliance will remain significant cost drivers.

By 2030, if graphene production, transfer/printing yields, and device standardization will improve as projected by industry reports, unit manufacturing costs for high-volume GFET sensors could reach single-dollar or sub-dollar levels for commoditized disposables or packaged sensors (excluding specialized readers), while fully validated clinical devices or wearable systems with integrated electronics will carry higher system-level prices, and overall cost declines will depend on achieving high yields, automated assembly, and broad supply chain scale. Demand is also expected to affect these costs.

If GFET biosensors prove to be as accurate as current laboratory diagnostic devices, the demand is expected to rise exponentially, further pushing down higher-volume manufacturing and cost reduction.

4.3. Conductive inks

Conductive inks based on graphene, MXenes, or graphene–MXene hybrids are printable formulations that deposit electronically conductive films or traces onto flexible or rigid substrates. They replace or reduce silver/copper in printed electronics by combining 2D conductive fillers (graphene flakes, few-layer graphene, or MXenes) with binders, solvents, and additives to produce inks that can be printed by screen, inkjet, aerosol-jet, or dispensing methods, and subsequently dried/annealed to yield low-resistance, mechanically robust conductive patterns [100].

These inks form electrical interconnects, antennas, sensors, heaters, electrodes, and current collectors that are used in flexible PCBs, RFID and NFC antennas, printed sensors and biosensors, and wearable e-textiles, among other applications. Graphene and MXene variants offer high mechanical flexibility, good sheet conductance in thin films, electrochemical activity (beneficial for electrochemical sensors), and low optical absorption, where transparent traces are required.

The primary inputs are conductive fillers such as graphite-derived graphene flakes or inks (CVD/chemically exfoliated graphene, rGO, and liquid-phase exfoliated graphene), MXenes ($Ti_3C_2T_x$ and related phases produced by selective etching and delamination), or engineered hybrids and composites mixed with silver, copper, or conductive polymers. The supporting components include solvents (water, alcohols, and glycols), polymeric binders/adhesives (polymers that balance conductivity and film formation), surfactants/dispersants/stabilizers, rheology modifiers, corrosion inhibitors (for copper), and functional dopants or nanoparticles when a higher conductivity or electrochemical activity is required.

4.3.1. Roadblocks/barriers

The key barriers to wider adoption are (a) scalable, cost-effective, and stable production of high-quality, low-defect graphene and MXene flakes with reproducible lateral size and surface chemistry, (b) long-term environmental stability (MXenes are oxidation-sensitive unless passivated, and graphene dispersions can aggregate), (c) formulation challenges to balance conductivity, print rheology, and adhesion without high-temperature sintering, (d) integration issues (compatibility with substrates and encapsulants, corrosion of metal co-fillers), and (e) supply chain and regulatory hurdles for new nanomaterial chemistries in consumer and medical applications. These challenges affect the yield, batch variability, and lifetime of real-world devices [101].

4.3.2. Technology evolution

By 2027, the expected maturation of printable graphene inks (improved solvent systems, photonic or low-temperature annealing, digital and/or 3D printing adoption) and broader pilot use of MXene inks (instead of only graphene-based inks), hybrid formulations that blend small amounts of silver or conductive polymers with graphene/MXene to reach

target conductivities at a lower cost, will proliferate, and manufacturing advances (aerosol-jet and roll-to-roll printing with tailored rheology) will push these inks from lab demos toward commercial pilot lines.

However, the next two years are expected to focus more on the development of inks and less on their commercialization. Standardization efforts for ink characterization and accelerated aging protocols are expected to increase.

The situation is expected to change by 2030. A large-scale supply of standardized graphene and stabilized MXenes, coupled with automated roll-to-roll coating and digital printing, should enable market penetration of wearables and printed sensors. Simultaneously, continued improvements in passivation chemistries for MXenes and hybrid strategies to reduce reliance on silver will make conductive inks cheaper and more robust, whereas advanced annealing (photonic, laser) and sinterless chemistries will open lower-temperature substrates and higher throughput. At that time, the sensors become more comfortable and sensitive.

4.3.3. Market & costs

The conductive ink market has grown significantly in recent years. It will grow from USD 3.62 billion in 2024 to USD 3.9 billion in 2025 at a CAGR of 7.9% [102]. This is expected to increase further by 2030, with a CAGR of 8.2%. Hence, the conductive ink market size is expected to be USD 4.6 billion and USD 5.8 billion, by 2027 and 2030, respectively.

The cost per kilogram for commonly used silver nanoparticle inks ranges between USD 1000 and 2500 kg^{-1} for small to medium purchase volumes (catalog prices illustrate this pricing band), while commercial graphene-based inks are typically sold at much lower raw material price points (supplier listings and small-volume catalog pricing imply tens to a few hundred USD per liter or per 100–1000 g depending on concentration and quality). MXene inks remain newer and typically command premium pricing during scale-up, although rapid cost reductions are reported at synthesis scales; practical per-unit printed trace costs depend heavily on solid loading, pattern density, and yield.

With moderate scale-up and improved MXene passivation and graphene production by 2027, the material costs for graphene-dominant conductive inks could decline substantially (single-to-two-digit percentage reductions), while MXene inks may become more price-competitive if etching/delamination processes are optimized. Hybrid inks that substitute a small fraction of silver with graphene/MXene reduce the per-trace metal cost, even if the total ink formulation cost remains comparable.

By 2030, standardized high-quality graphene and stabilized MXene production should drive raw material price declines, allowing graphene/MXene-based inks to be cost-effective substitutes for some silver applications; for commoditized printed traces, per-kg equivalent formulation costs could fall to levels that make graphene/MXene hybrids broadly attractive, whereas premium specialty inks (high-conductivity, low-temperature cure, electrochemically active) retain a price premium justified by performance. The final end-product cost will remain driven by the processing, yield, and regulatory/qualification overhead rather than the raw ink price alone.

4.4. Triboelectric nanogenerators

Triboelectric nanogenerators (TENGs) convert mechanical motion (contact, sliding, vibration, or fluid flow) into electrical energy through contact electrification and electrostatic induction [103]. In TENGs, the two contacting layers are typically selected to be widely separated in the triboelectric series (i.e. strong electron-donating vs strong electron-withdrawing tendency), most commonly using dielectric polymers (e.g. fluorinated polymers and silicones on the negative side and more electron-donating polymers such as polyamides on the positive side) [104]. Conductive layers are then integrated as charge-collecting electrodes, implemented as metal foils/meshes, or as flexible, solution-processable conductors (including graphene- and 2D-material-based films/inks), whereas mechanical supports and encapsulation materials (textiles, elastomers, PET, PU, etc) provide robustness and wearability [105]. When graphene [106], MXenes [107], and graphene–MXene hybrids are used, they typically serve as flexible electrodes, charge-trapping layers, or friction/tribo-layers that increase surface charge density, improve conductivity, and enable flexible, lightweight device architectures for wearable, structural, and environmental energy harvesting and self-powered sensing [105, 108].

The primary functions of the TENG are as follows: (a) harvesting ambient mechanical energy (human motion, machine vibration, airflow, and water waves) and storing or conditioning the energy for low-power electronics and (b) supplying self-powered sensing signals (impact, pressure, motion, flow, and corrosion), where the generated voltage/-current is read directly or used to drive wireless microelectronics. Graphene and MXene additions boost the output (higher charge density and faster charge transfer), add mechanical robustness, and permit transparent or stretchable form factors for wearables and embedded systems/devices.

4.4.1. Roadblocks/barriers

The main barriers for TENGs, regardless of whether they employ graphene, MXenes, or other advanced materials, stem from the inherent challenges of the technology itself: their electrical output is often unstable owing to surface wear, charge decay, and

strong sensitivity to environmental factors such as humidity and contamination, which degrade long-term durability; their irregular, high-voltage, but low-current signals require sophisticated power management and conditioning to be usable, yet efficiency losses remain significant, and their average power density is generally too low to support continuous operation of most devices, confining them mainly to niche low-power sensing applications unless breakthroughs in materials, encapsulation, and system integration are achieved.

Other barriers to TENG technology include limited and highly variable power output under real-world, irregular mechanical inputs, strong dependence on environmental conditions (especially humidity and surface contamination) that shift tribocharge behavior and accelerate performance drift, surface wear, and material fatigue from repeated contact, which degrade charge density and change interface morphology, charge leakage, and electrostatic screening that cap achievable energy density and complicate stable long-term operation, difficulty in scaling devices while maintaining uniform contact mechanics and consistent triboelectric properties across large areas, impedance mismatch between high-voltage/low-current TENG outputs, typical electronics that necessitate efficient rectification and power-management circuits with low-loss energy storage integration, challenges in standardizing performance metrics and test protocols that make comparisons and design rules less transferable, and packaging/encapsulation trade-offs, where protecting the active surfaces often reduces triboelectric effectiveness or introduces mechanical constraints that lower harvested energy [109].

4.4.2. Technology evolution

By 2027, the broader adoption of MXene and/or graphene composites in targeted TENG demonstrations (wearables, shoe-embedded harvesters, structural sensors, IoTs, etc) is expected to be driven by improved MXene passivation chemistries and hybrid composite strategies that combine low-cost polymers with 2D fillers for higher charge density. Manufacturing will move from a one-off lab assembly to semi-continuous processes (electrospinning, roll-to-roll coating, and spray patterning), and integrated power-management modules will become more common in demonstration products. Performance improvements will focus on humidity mitigation, surface nanotexturing, and integration with low-power wireless modules.

By 2030, if the supply chain scale and material stability challenges are addressed, MXene/graphene-enhanced TENGs should reach commercial maturity in defined niches (self-powered wearable sensors, distributed IoT sensors, etc). Standardized fabrication processes, certified accelerated-aging data, and compact power conditioning plus energy storage stacks will allow system integrators to specify TENG modules, such as lithium-ion cells, enabling broader deployment where maintenance-free, distributed energy harvesting is valuable.

4.4.3. Market & costs

The global triboelectric nanogenerator market size is estimated at USD 160 million in 2024 and is expected to reach USD 347.5 million and USD 754.6 million by 2030, respectively, growing at a CAGR of 29.5% [110]. Self-powered electronics are becoming more popular, which is the main reason why the TENTGs market is growing. Because more electronic devices are being made small and popular, there is a growing need for energy that is small and does not need to be up kept.

As the market (and demand) increases, the cost of TENGs will be reduced, from the current range of EUR 20–200 for wearable/portable TENGs to EUR 15–150 by 2027, and EUR 10–105 by 2030. Under optimistic scaling and process-improvement trajectories, high-volume TENG modules that use inexpensive polymer matrices and scaled graphene/MXene fillers could reach material and manufacturing costs that may enable less than USD 10 incremental costs for very simple harvesters (e.g. embedded shoe insole sensors), whereas integrated modules with conditioning electronics and energy storage will remain higher priced but competitive for specialized industrial or medical sensing use cases.

5. End-use—biomedical applications

The growing burden of infectious diseases, chronic conditions, and emerging pandemics has accelerated the demand for rapid decentralized testing to reduce reliance on centralized laboratories, enable timely treatment decisions, and improve healthcare services.

Simultaneously, rising healthcare costs and pressures to reduce hospital visits encourage the use of POC tools in home care and resource-limited settings, while global health initiatives increasingly prioritize diagnostics that are affordable, robust, and scalable.

Additionally, patient-centric trends, such as personalized medicine, real-time monitoring, and preventive care, are expanding POC applications beyond infectious diseases to oncology, cardiovascular monitoring, and metabolic disorders. Regulatory support and increased investment from both public and private sectors further strengthen the momentum for adoption.

5.1. PoC *in-vitro* diagnostics & monitoring

PoC measurement of the concentration of targeted analytes in bodily fluids (CSF, blood, sweat, etc) is one of the most promising applications of 2DM-based

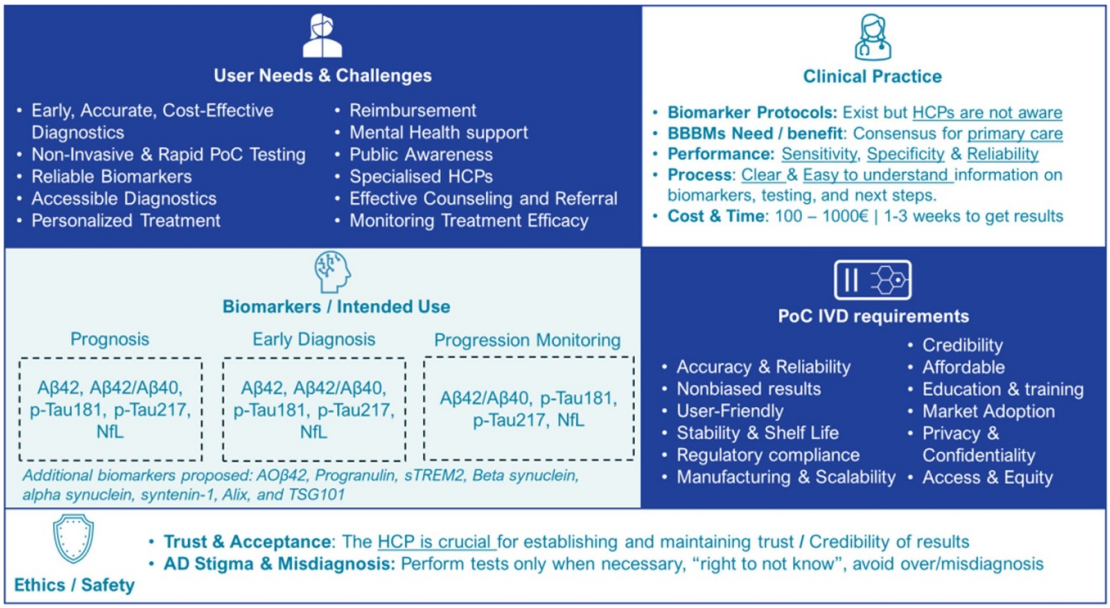

Figure 2. Main user needs, challenges and PoC IVDs requirements for AD diagnostics. Reproduced from [49]. CC BY 4.0.

biosensors using either electrochemical or GFET biosensing components.

PoC IVDs have immense potential, with several applications, including supporting disease prognosis, early detection, disease progression, and/or treatment efficacy monitoring. Their low-cost and miniaturized design makes them ideal for widely accessible PoC testing. This is of growing interest, especially for diseases such as Alzheimer's disease (AD), where prevention and early detection that will allow access to new treatment options are not yet accessible to the public.

In a recent study by 2D-BioPAD [49], a range of requirements has been identified by a diverse pool of stakeholders for a PoC device for detecting biomarkers valuable for AD (figure 2), showing the complexity of such a biomedical application.

5.1.1. Roadblocks/barriers

Specificity and sensitivity are the core challenges, since the detection of each biomarker must be accurate (>85%) and sensitive (e.g. femtomolar LoD for AD biomarkers) to have clinical value in most cases (this depends highly on the disease and target analyte).

As these devices/decision support tools are still under rigorous development, aspects such as large-scale manufacturing, reimbursement, and long-term sustainability have not yet been fully explored, and may hinder their market uptake.

In addition, regulatory compliance and clinical validation require significant resources (3–10 years) before clinical adoption.

5.1.2. Market & costs

The global PoC diagnostics market size was estimated at USD 47.8 billion in 2024 and is projected to reach USD 68.5 billion by 2030, growing at a CAGR of 5.8% from 2025 to 2030 [111]. The main drivers of this growth are clinical, technological, and socioeconomic factors that emphasize speed, accessibility, and personalized care.

Current diagnostic pathways are heavily dependent on centralized laboratories, with fluid-based biomarker testing costs varying significantly, from a few EUR to several hundred per biomarker. Waiting times are also an issue, since the results can take a few hours (although most devices can deliver results from 30 min, they usually require a minimum number of samples to run a test to be cost-effective) to a few days (if there is a need to visit an external, often private, lab).

As new tests become available (e.g. Lumipulse G ptau217/ß-amyloid 1–42 a few months ago [112]), the cost of testing is expected to decrease.

5.2. Bioelectrical signal sensing—electromyography (EMG) and electroencephalography (EEG)

2DM–based EMG or EEG sensors use ultrathin conductive layers (such as graphene and MXene) to detect muscle or brain electrical signals (respectively) with high sensitivity, flexibility, and conformability. These materials enable wearable, stretchable, and skin-compliant sensors that outperform conventional metal- or gel-based electrodes in terms of comfort and mechanical resilience, while offering more miniaturized ergonomics that significantly support on the one hand neuromuscular disease diagnosis, rehabilitation monitoring, and prosthetic control, and on the other hand neurodegenerative disease diagnosis, cognitive performance, and sleep disorders (among others).

5.2.1. Roadblocks/barriers

The main challenges include achieving consistent skin–electrode contact during movement, motion, and sweating; ensuring long-term skin compatibility and adhesion; preventing signal noise and motion artifacts; stabilizing 2DM against oxidation or degradation; and scaling manufacturing to produce reproducible, safe, and cost-effective wearable patches.

In addition, unresolved issues, such as signal noise/motion artifacts, electrode placement, patient discomfort, and complex data analysis, are challenges that remain unaddressed and may hinder clinical integration and adoption.

Reparability, recyclability, and complete decomposition are still under investigation to enable more sustainable solutions (either single-or multiple-use).

5.2.2. Market & costs

In 2025, the broader EMG device market is valued at approximately USD 1.0 billion, driven by clinical and rehabilitation demand. The market is expected to expand at 6.6% CAGR, reach USD 1,41 billion by 2030 [113]. With a higher CAGR of over 10%, the market size of portable EEG devices was estimated at USD 0.8 billion in 2025 and is expected to reach over USD 1.9 billion by 20 233 [114]. The specific niche of 2D material-based EMG sensors, however, remains predominantly in the research and prototype stages, with limited commercial traction.

By 2027, the ongoing interest in wearable health monitoring, sports, and prosthetics, coupled with advances in flexible electronics, may allow 2D-based EMG sensors to capture commercial share.

By 2030, assuming the wide adoption of wearable health-monitoring ecosystems and successful standardization, 2DM-based EMG sensors could occupy mid-hundreds-of-millions to low-billion-USD segments within the total EMG and wearable sensor market, particularly in applications such as smart prosthetics, long-term rehabilitation, and consumer wearables.

5.3. Cardiovascular monitoring—electrocardiography (ECG)

Portable ECG devices are compact systems designed to monitor and record electrical activity of the heart outside traditional clinical settings. Unlike the conventional ECG machines used in hospitals, portable devices can be worn or carried by individuals in daily life, allowing continuous or on-demand cardiac monitoring. These devices range from handheld sensors and wearable patches to smartwatches with integrated electrodes. They provide valuable information on heart rhythm, detect arrhythmia, monitor recovery after cardiac events, and support preventive health care. Their portability and ease of use make them particularly important for remote health monitoring, personalized medicine, and early detection of cardiovascular disorders while also reducing the burden on healthcare systems by enabling home-based diagnostics.

The integration of 2DM into portable ECG devices provides opportunities for improved performance and comfort. Graphene and other 2DM offer high electrical conductivity, flexibility, and transparency, making them suitable for developing lightweight skin-conformable electrodes and sensors. Traditional gel-based electrodes can cause skin irritation and degradation with long-term use, whereas 2DM-based electrodes can provide stable, high-quality signal acquisition without the need for gels. Their mechanical flexibility ensures better contact with the skin, even during movement, which reduces motion artifacts and improves the reliability of the readings.

In addition, 2DM enables the development of thin, stretchable, transparent devices that can be seamlessly integrated into clothing or wearable patches. These advances could make portable ECG devices more durable, comfortable, and capable of long-term continuous monitoring, ultimately enhancing the patient compliance and diagnostic accuracy.

5.3.1. Roadblocks/barriers

The main barriers to applying 2DM to ECG are scalability, stability, and integration. Producing large-area, defect-free, and reproducible films of graphene, MXenes, or other 2DM remains difficult, and variations in quality directly affect the electrode performance. Long-term stability and biocompatibility are also unresolved, as sweat, oils, and body motion can degrade materials, compromise skin–electrode adhesion, and reduce signal fidelity. However, the long-term safety of continuous skin contact remains underexplored.

Beyond material challenges, practical deployment faces hurdles in ensuring mechanical robustness on dynamic skin surfaces, maintaining low-impedance electrical performance under real-world conditions, and preventing motion artifacts. Cost, lack of standardized testing, and slow regulatory acceptance further limit commercialization compared to mature alternatives, such as conductive polymers or metal-coated textiles. Together, these barriers must be addressed through advances in scalable synthesis, hybrid designs, encapsulation methods, and clear medical certification pathways before 2D-material-based ECG devices can be widely adopted.

5.3.2. Market & costs

Current evidence points to a fast-growing addressable market for portable/mobile ECG devices with the limited but emerging use of 2DM-based electrodes. Using the most specific segment (mobile ECG) as the anchor, the global mobile ECG devices market size

was estimated at USD 2.26 billion in 2022 and is projected to reach USD 5.42 billion by 2030, growing at a CAGR of 11.7% from 2023 to 2030 [115].

The global ECG equipment market size was estimated at USD 8.62 billion in 2023 and is projected to grow at a CAGR of 7.2% from 2024 to 2030. The increasing prevalence of cardiovascular diseases worldwide, coupled with the growing geriatric population, is a primary factor that contributes to market growth.

Device costs today (2025) range from EUR 70–150 for approved single-/six-lead consumer handhelds (e.g. KardiaMobile) and USD 399+ for smartwatches with ECG; disposable Ag/AgCl electrodes for patches are ∼€0.50 per unit (packs of 50 ∼EUR 25). These (already quite low) costs are expected to drop further by 2030, with improvements in ergonomics and sensitivity of devices. The main value of 2DM-based solutions is the need for better ergonomics (e.g. inks on e-textiles) combined with higher wear time and lower re-use/maintenance, offering a competitive advantage to already cost-effective solutions.

5.4. Brain computer interfaces (BCIs)

BCIs are systems that enable direct communication between the brain and external devices, bypassing conventional neuromuscular pathways. They operate by detecting and decoding neural signals, such as the electrical activity recorded through electrodes, and translating them into commands for controlling computers, prosthetics, or other assistive technologies. BCIs can be invasive, with electrodes implanted directly into brain tissue, or non-invasive, using methods such as EEG.

Their applications span medical rehabilitation, neuroprosthetics, communication aids for individuals with severe motor impairments, and increasingly, human–machine interaction in broader contexts, such as gaming, education, and industrial systems.

The integration of 2DM into BCIs offers promising advances owing to their unique electrical, mechanical, and chemical properties. Materials, such as graphene, combine high conductivity, mechanical flexibility, and biocompatibility, making them suitable for constructing ultrathin, lightweight, and conformable neural electrodes. These electrodes can achieve higher signal-to-noise ratios and improved spatial resolution compared to traditional metal-based electrodes, enhancing the fidelity of neural recording and stimulation.

Additionally, the flexibility of 2DM allows the electrodes to better match the soft, curved surface of the brain tissue, reduce inflammatory responses, and improve long-term stability. Beyond sensing, 2DM can also facilitate novel functionalities such as integrated photonic or chemical sensing, opening pathways for multimodal BCIs that couple electrical activity with metabolic or molecular readouts.

5.4.1. Roadblocks/barriers

Key barriers include long-term stability and robustness at the skin interface (sweat, motion, and drying artifacts), oxidation and environmental degradation of some 2DM (notably MXenes) without passivation, batch-to-batch variability in material synthesis and printing, and the need for scalable, biocompatible manufacturing with reproducible impedance and noise. Regulatory and clinical validation pathways for new materials and device formats remain a major translational hurdle (especially for invasive BCIs).

5.4.2. Market & costs

The global invasive BCI total addressable market is estimated at USD 160.44 billion in 2024 and is expected to grow at a CAGR of 1.49% from 2025 to 2030. Several studies have reported that invasive BCIs offer greater assurance of restoring motor function and communication in patients with conditions such as amyotrophic lateral sclerosis, spinal cord injuries, and stroke [116].

On the other hand, the overall EEG devices market (subset of the BCI market) was estimated at around USD 1.2 billion in 2023 and is projected to reach USD 2.39 billion by 2030, growing at a CAGR of 10.36% from 2024 to 2030, driven by the increased neurological disease burden and the adoption of wearables.

Within these markets, 2D-material electrodes are still in the pre-commercial to early commercial stages (pilot clinical/wearable studies, developer kits), with most revenue still concentrated in traditional wet/dry systems.

6. AI for 2DM-based biosensors

AI-driven methods have revolutionized material discovery structure generation, property prediction, high-throughput screening, and computational design, while advancing development through improved characterization and autonomous experimentation [117]. Advanced ML, deep learning (DL), and the most recent generative AI (GenAI) and foundation models have the potential to transform this landscape by providing significantly more efficient approaches for designing and optimizing 2DM and their components across domains, including sensors for biomedical applications. In the following subsections, we focus on key aspects that will be pivotal in the next few years.

6.1. ML for 2DM synthesis and characterization optimization

Advanced ML models can estimate the optimal synthesis conditions (e.g. temperature, precursor concentration, pressure, and reaction duration) to achieve targeted 2DM characteristics, including, but

not limited to, the number of layers, defect density, conductivity, and surface area. By doing so, these models can predict experimental conditions for optimized 2DM with tailored properties (higher conductivity for electrochemical sensors, larger surface area for improved biomolecule immobilization, etc) that complement or even replace traditional resource-intensive trial-and-error experimentation pipelines. In addition, ML can be used to process and interpret complex data from characterization techniques (e.g. Raman spectroscopy and XPS) to identify key features, assess performance, detect anomalies, and interpret the data.

6.1.1. Roadblocks/barriers

As in most industries, high-performance models require large, diverse, and rigorously curated experimental datasets, which remain limited in availability. Simultaneously, variability in synthesis and characterization protocols and processes across laboratories reduces dataset consistency and hampers model generalization.

6.1.2. Technology evolution

With sufficiently curated datasets, ML workflows can reach, by 2027, accuracy levels of approximately 90% in predicting synthesis–property relationships by 2027. This performance is expected to be pushed beyond 95% accuracy by 2030, considering the exponential improvements in model architecture and availability of expanded datasets by 2030. The emergence of material-focused foundation models is expected to transform new material discoveries, further pushing the capabilities (and uses) of AI in this domain.

6.1.3. Market & costs

ML for material discovery and optimization is a part of the broader field of AI in materials informatics, particularly in the chemical industry. In 2025, the broader AI in chemical and material informatics market is estimated near USD 17.1 billion in 2025, reflecting industry recognition that ML enhances efficiency and innovation in materials R&D, including 2DM synthesis optimization [118]. Following an exceptional CAGR of 40.66%, the adoption of ML tools for materials R&D and synthesis optimization is expected to reach approximately USD 34 billion by 2027, and more than USD 180 billion by 2030.

Although the use of ML (and AI in general) is not novel in this domain, most applications are based on custom models that are tailored to a specific task or process. Hence, a new ML-based approach for optimizing the synthesis of 2DM is currently valued at USD 200 K. As more (pre-trained) models become available (open-source or through publications), the cost is expected to decrease by approximately USD 50 thousand by 2027. By 2030, the cost may drop significantly (e.g. USD 10–15k) with the introduction of AI Agents and potentially of Artificial General Intelligence).

6.2. DL biosensor design

DL-driven design for 2D-materials biosensors applies neural networks (CNNs, GNNs, MLPs, and physics-informed architectures) to accelerate and automate key design steps [119], predict material properties and surface chemistries, optimize device geometries and optical/electrical readout layers, denoise and process sensor signals, and close the loop between experiments and synthesis using active learning. This allows teams to explore large, coupled parameter spaces (material composition, layer thickness, functionalization, microstructure, and device layout) far faster than manual or purely physics-based approaches, enabling higher-sensitivity application-tailored biosensors based on graphene, TMDs, MXenes, and hybrids.

6.2.1. Roadblocks/barriers

Major barriers include the scarcity and heterogeneity of high-quality labeled data (many groups publish limited, non-standardized characterization), domain shift between simulated and experimental data, difficulty integrating noisy real-world measurements into DL pipelines, the need for explainable and physics-consistent models (to gain experimentalists' trust), computing and infrastructure costs for training large models, the organizational friction of embedding DL into existing lab workflows, and regulatory and IP complexities when models guide clinical-grade sensor design. Overcoming these challenges requires standardized datasets, robust uncertainty quantification, active-learning experiments, and closer integration of automation, instrumentation, and model development.

6.2.2. Technology evolution

From 2025 to 2027, DL for 2D-materials biosensor design will move from exploration and expert-driven use toward semi-standardized, workflow-integrated adoption. The focus will be on improving data quality and usability rather than developing radically new algorithms: curated multimodal datasets (synthesis parameters, Raman/XPS spectra, electrical/optical responses), transfer learning across graphene, MXenes, and TMDs, and physics-informed neural networks that embed electrochemical and surface-interaction constraints. It is estimated that the accuracy will increase by over 85% on the predicted biosensor features, while reducing the computation time for simulations by at least 50%.

Accuracy is expected to reach over 90% by 2030 owing to the integration of DL techniques with lab automation, digital twins, and edge-AI signal interpretation. Explainable AI, uncertainty quantification, and validation against clinical datasets will become

critical enablers for regulatory acceptance, whereas model outputs will become increasingly embedded intellectual property within commercial biosensors rather than standalone software products.

6.2.3. Market & costs

The DL market aligns with the materials informatics market as described in section 6.1.3. The costs follow a similar scale, with a significant reduction expected within the next five years.

6.3. AI-driven biosensor signal processing and interpretation

The use of AI methods to transform raw biosensor outputs (electrochemical currents, impedance spectra, optical signals, mechanical strain, or multimodal data) into reliable, clinically or operationally meaningful information has gained increased momentum. AI models are used to denoise signals, correct baseline drift, compensate for motion and environmental interference, extract features automatically, classify analytes or physiological states, and estimate uncertainty in real-time. This approach is increasingly critical for wearable, PoC, and multiplexed biosensors, where signals are weak, variable, and context-dependent and where classical threshold-based processing is insufficient. Thus, AI has become a core layer that enables higher sensitivity, specificity, and robustness, without changing the underlying sensor hardware.

6.3.1. Roadblocks/barriers

The key barriers include the limited availability of large, high-quality labeled biosensor datasets; strong variability between users, environments, and sensor batches; and difficulties in transferring models from controlled laboratory data to real-world conditions. Power consumption and latency remain constraints for edge AI deployment, particularly in wearable or implantable systems. From a translational perspective, the lack of transparency in AI models (particularly in DL) complicates trust, validation, and regulatory approval for medical applications. Data privacy, cybersecurity, and interoperability with healthcare IT systems may further slow adoption, whereas the need for multidisciplinary expertise (AI, biosensing, and regulatory science) raises development costs.

6.3.2. Technology evolution

By 2027, AI-driven signal processing is expected to shift from offline analysis to embedded and edge-AI implementations, enabling real-time high-quality interpretation (e.g. >90% accuracy in detecting biomarkers) directly on biosensor devices or gateways. Hybrid models that combine physics-based signal models with neural networks will improve generalization and reduce training data requirements, whereas transfer learning will allow algorithms trained on one sensor platform to adapt to others. Multimodal fusion (e.g. combining electrochemical and physiological context signals) will become more common, particularly in wearable and PoC diagnostics.

By 2030, AI-based interpretation is likely to be the default standardized component of biosensor systems, with higher accuracy levels ($\geqslant$95% detection rate of biomarkers). Explainable AI, uncertainty quantification, and adaptive algorithms that dynamically tune sensor operations based on signal quality will be widely deployed, supporting regulatory approval and long-term autonomous operation. At this stage, AI will not only interpret signals, but may also actively co-optimize sensing strategies in closed-loop systems.

6.3.3. Market & costs

The global AI in the diagnostics market was valued at USD 7.03 billion in 2025 [120]. The market is projected to grow with a CAGR of 46%, reaching USD 14.98 billion in 2027 and USD 46.63 billion by 2030. Within this rapidly growing market, AI-driven signal processing and interpretation constitute a significant portion ($\sim$30%).

In terms of costs, as in other cases, a solution from scratch is currently required, often reaching a budget exceeding several hundred thousand dollars to model a tailored model. With the emergence of foundation models in the domain, this cost is expected to drop significantly in the coming years, reaching only a few thousand dollars by 2030 (mainly considering that certification costs for medical devices will remain resource-intensive).

6.4. Integrated AI chip

Integrated AI chips in biosensors refer to the embedding of dedicated AI hardware (e.g. edge-AI accelerators, neural processing units or system-on-chip units, and neuromorphic chips) directly within sensing devices, such that signal processing, pattern recognition, calibration, anomaly detection, and decision-making occur at the sensor (on edge) rather than in distant servers. These chips enable the real-time interpretation of biosensor outputs (electrochemical, optical, or physiological signals) with low latency, improved power efficiency, and reduced reliance on cloud connectivity, which is crucial for wearable PoC and autonomous diagnostic systems. Embedded AI chips convert raw biosensor data into 'on-device' actionable insights, enhancing sensitivity and specificity while maintaining the privacy and responsiveness typical of edge computing.

6.4.1. Roadblocks/barriers

Integration faces several barriers, including, but not limited to, power and energy constraints in miniaturized biosensor form factors, data scarcity and variability across users and conditions that complicate on-device model generalization, hardware–model co-design complexity to balance computing capability

with low energy budgets, standardization and interoperability across chip and biosensor ecosystems, and regulatory/clinical validation when AI chips are part of medical devices. Ensuring consistent and secure firmware and protecting sensitive health data processed on edge chips add further complexity.

6.4.2. Technology evolution

By 2027, the integration of AI chips into biosensors is expected to follow broader trends in the edge of the AI chip market, where devices will migrate from cloud-dependent analytics to -device inference engines. Edge AI processors (particularly neuromorphic chips) capable of low-power inference will become more prevalent in biosensing platforms, supporting real-time preprocessing and classification directly for wearables and handheld diagnostic tools. These chips use optimized neural architectures and quantization techniques to handle biosignal complexity at milliwatt-power levels.

By 2030, this evolution will lead to ubiquitous -device AI, with specialized ultralow-power AI silicon (dedicated neural accelerators or neuromorphic chips) embedded in mainstream biosensor products, enabling advanced functions such as adaptive calibration, multimodal signal fusion, and incremental on-device learning. This trajectory reflects the broader expansion of edge AI markets and chip innovation driven by IoT and biosignal processing needs.

6.4.3. Market & costs

The edge AI chip market (mainly hardware) is estimated to be USD 3.7 Billion by 2025 [121]. As biosensors increasingly embed such chips, a growing share of the market will overlap with biosensor hardware and analytics revenues. Simultaneously, the overall edge AI market (encompassing hardware, software, and services for -device intelligence) is estimated at approximately USD 25.3 Billion in 2025 [122].

Both markets are expected to grow with a CAGR of approximately 21.6%, reaching market sizes of USD 9.75 Billion and USD 66.5 Billion, by 2030 respectively. Within these expanding markets, the demand for AI chips in biosensors could represent a billion-dollar niche, as manufacturers embed AI capabilities for real-time diagnostics and wearables.

As more AI chips become available, the cost of both hardware and software is expected to drop significantly in the coming years. There are already available solutions in the market (e.g. AI accelerators that cost from several hundred to thousands of euros); however, they are mostly bulky components that cannot be easily integrated into small-factor biosensors. For these chips, custom AI models are most often required, maintaining modeling costs in hundreds of thousands of euros when developed from scratch. Within the duration 2027–2030, more AI chip technologies will become available, whereas software implementation will focus more on model adaptation than implementation from scratch, reducing the costs in both cases by an order of magnitude.

7. Discussion

The rapid expansion of 2DM research has clearly demonstrated its potential to redefine biomedical sensing performance. However, progress toward real-world deployment will depend less on isolated demonstrations of record sensitivity, and more on addressing system-level challenges. A central issue is the reproducible synthesis of 2DM with controlled thickness, defect density, surface termination, and batch-to-batch consistency. Without standardized material specifications, a meaningful comparison between sensing platforms and reliable scale-up remains difficult.

Equally critical is the engineering of stable and selective bio-interfaces. While the large surface area of 2DM enables high analyte loading, it also increases the susceptibility to nonspecific adsorption and biofouling. Future research should prioritize surface functionalization strategies that balance sensitivity with long-term stability in complex biological fluids. Advances in passivation layers, antifouling coatings, and bio-inspired interfaces are expected to play decisive roles, particularly in continuous and wearable sensing applications.

From a device perspective, integration with microelectronics, microfluidics, and data processing hardware represents both major opportunities and challenges. 2DM is inherently compatible with flexible and low-power electronics; however, large-area fabrication and reliable interfacing remain immature. Progress in printing techniques, wafer-scale growth, and heterogeneous integration is essential to bridge the gap between material innovation and manufacturable sensor systems. Simultaneously, data reliability, calibration protocols, and benchmarking against existing clinical standards must be established to build confidence among end users.

Looking ahead, the most impactful advances are likely to arise from convergent approaches that combine 2DM with AI, multiplexed sensing architectures, hybrid material systems, and other key enabling technologies, such as AM. Rather than competing with established technologies on a single performance metric, 2DM-based sensors are poised to enable new sensing paradigms such as real-time, decentralized, multiplexed, and personalized diagnostics. Achieving this vision will require close collaboration between material scientists, engineers, biologists, clinicians, and industry stakeholders. This Roadmap highlights that, while significant challenges remain, the foundational knowledge and momentum now in place position 2DM are key enablers of next-generation biomedical sensing technologies.

Table 3. Strengths, weaknesses, opportunities, and threats of 2DM-based biosensors.

Strengths	Weaknesses	Opportunities	Threats
Lower cost	LoD still not at attomolar detection levels	Improved ML/AI-based models for materials	Demanding regulatory compliance/certification process
Faster results	No distribution channels available	Aging population	Competing technologies in the market
Better ergonomics	Batch to batch variability of raw materials	Resistant pathogens	Unclear reimbursement potential
Digitalized outcome	Oxidative instability	Foundation models for material sciences	Environmental impact of upscaling 2D Material production
Multifunctionality	Uncertain biocompatibility	EU strategies to boost biotechnology	Lack of standardized specifications
Easy to form polymer composites for light weight applications	Limited safe and sustainable by design large scale production	New medications/vaccines require more advanced screening/monitoring technologies Increased needs for remote patient care New enabling technologies (AM, AI, etc)	

The key drivers for using 2DM in biosensors are both technological and economic. In the long term, an established production guideline and framework for clean industrial processes and sustainability, using a safe and sustainable design (SSbD) methodology throughout the whole value chain, will allow 2DM to conquer a significant portion of the biosensing markets.

In the following subsections, we summarize the main Strengths, Weaknesses, Opportunities and Threats of the 2DM analyzed in this study, followed by an analysis of the value chain and a concise roadmap up to 2030.

7.1. SWOT analysis

To contextualize the scientific and technological maturity of 2DM in biosensing and to inform future research and translation pathways. This framework provides a balanced assessment of intrinsic material advantages along with current technical limitations. By mapping these internal factors against external drivers, SWOT analysis offers a concise yet comprehensive perspective on the strategic position of 2DM in biosensing.

7.2. Value chain analysis

This section integrates the information from previous chapters to produce a value chain analysis in the vast field of biomedical sensors. Table 3 summarizes strengths, weaknesses, opportunities, and threats of 2DM-based biosensors.

Materials, components, applications, and AI are integrated solutions to future health challenges. To produce this value chain analysis, the following activities took place: review, consolidation, and comparison of information, clustering of best practices, gap analysis, identification of potential constraints, identification of the required actions for each gap, and identification of potential opportunities. The value chain analysis consists of following the different processes and their advancement from an initial 'state-of-the-art TRL' to a 'closer to the market MRL' by understanding roadblocks and barriers (gaps) versus the technology evolution fit (solutions).

The biomedical sensors value chain analysis is performed from three different perspectives:

- Process value chain: detailing the interrelations, complementarities, and synergies among materials, components, applications, and AI.
- Technology value chain: detailing the capacity to eliminate gaps and barriers to meet the best maturity level and the balance between technology push and market pull.
- Exploitation value chain: detailing technology integration, innovation management, business cases, and other factors (externalities).

7.2.1. Process value chain

The interrelation balance (critical mass, added value, complementarities, and synergies) among materials, components, biomedical applications, and related AI-driven methods is of fundamental importance in producing and optimizing sensors (table 4). Biomedical applications require efficient components to ensure biosensing activities in different environments, and these components require enhanced materials to ensure the sensing quality. The increasing need for 'usable data' moving in the value chain has now opened the door to AI tools as a support.

Table 4. Interrelations across the process value chain of 2DM-based biosensors.

Materials	Components	Applications	AI
Increased electrical properties Better mechanical stability Mimic antibodies	Selective recognition. Rapid quantitative readouts	PoC multi biomarkers measurement needs	Synthesis and characterization optimization
High biocompatibility Low toxicity	Multiplexed sensing	Ergonomic ultrathin wearable sensors	New material discoveries
Scalability	Electrical interconnection	Ultrathin, lightweight and comfortable neural electrodes	Accuracy to reach over 90%
	Improved conductivity		*In-silico* embedded

Table 5. Technology maturity required for 2DM-based biosensors.

Materials	Components	Applications	AI
More scalable and affordable	Enhance sensitivity	Increase biomarkers specificity-sensitivity	Process and interpret complex data
Achieve efficient green reduction	Enlarge # of analytes	Optimize large-scale manufacturing	Close the loop between experiments and synthesis
Improve stability & reproducibility	Reduce device variability and cost	Strengthen long-term sustainability	Estimate uncertainty in real time
Boost simultaneous detection of multiple targets	Foster hybrid strategies	Ensure reimbursement	Real-time-low latency connectivity interpretation
	Address supply-chain scale and materials stability to reach commercial maturity	Increase regulatory compliance and clinical validation	

The sensing capacity of 2DM is essential for identifying biomarkers that provide crucial data for medical diagnostics and therapy for a wide range of pathologies. The increasing quantity of data and digital information processing can be managed only by integrating AI-based methods and tools.

7.2.2. Technology value chain

Technological maturity (table 5) in this sector depends on the capacity to eliminate gaps and barriers to meet the highest maturity level of materials, components, and AI to get closer to the biosensing capacities that meet the market pull of an increasingly growing health sector. More sensitive materials allow for the increased sensitivity of components that ensure more precise health diagnostics and therapies in an optimal digital and data environment.

2DM must be more scalable and stable to permit components to increase the sensitivity of an ever-enlarging analyte environment, thus enabling applications in the health sector to be more biomarker-specific and integrated with large-scale manufacturing processes. AI to reduce gaps in complex data analysis, real-time status, and uncertainty.

7.2.3. Exploitation value chain

The technology exploitation capacity of this sector depends on the successful integration of materials, components, applications, and AI into intelligent biosensors with high added value for the biomedical and health sectors (table 6). These must be solutions that address problems and meet market needs and user requirements by being cheaper, faster, and better. Costs are expected to decrease, while the market size is expected to increase.

As such, the health biosensor market is moving from a fragmented and dispersed situation to a more consolidated and integrated prospective market, where permanent sensors are embedded in all human activities, from PoC to wearable, from personalized health to preventive medicine.

7.3. 2030 roadmap

Tables 7 and 8 illustrate the coordinated evolution of materials, components, applications, and AI enabling technologies from 2025 to 2030. In the near term (2025), most 2DM-based biomedical sensing technologies will remain in the advanced laboratory or early prototype stages. Graphene, GO, and rGO are already widely used in proof-of-concept sensors, benefiting from established synthesis routes and relatively mature processing methods. In contrast, MXenes offer superior electrochemical performance but face challenges related to oxidation, reproducibility, and scalable synthesis. At the system level, electrodes, inks, and microfluidic channels are primarily used in research environments, whereas applications such as PoC diagnostics, EMG, ECG, and BCIs remain largely pre-commercial.

By 2027, the roadmap anticipated a transition from isolated demonstrations to integrated and reproducible systems. Advances in scalable and safer synthesis methods, improved material stability, and

Table 6. From technology pull to market pull for higher market penetration of 2DM-based biosensors.

Technology integration	Innovation management	Business case	Related factors
Solid research pipeline capability	Materials segmentation	Solution fit	Digitalization & AI
Validated technology maturity	Components differentiation	Capacity fit	Green dimension
Seamless integration & prototyping	Applications positioning	Market fit	Training needs & specialization
High added value & usefulness	Artificial Intelligence acceleration	Business model fit User requirements Market demand size Emerging trends	Regulation & standardization
Technology Push TRL			**Market Pull** **MRL**

Table 7. 2025–2030 roadmap for materials, components, and biomedical applications (materials and components).

	2025	2027	2030
Graphene	Mature lab-scale synthesis; high-quality films for sensors; early standardization efforts	Scalable, reproducible large-area graphene; improved transfer and integration	Industrial-scale production with standardized specs; widespread use in commercial biosensors
GO	Widely used for functionalization and composites; variability in oxidation level	Better control of oxygen content and batch reproducibility	Optimized GO grades tailored for specific biointerfaces and sensing roles
rGO	Cost-effective conductive material; moderate performance variability	Improved reduction methods yielding higher conductivity and stability	Reliable rGO inks and films for mass-produced sensing components
MXenes	High-performance prototypes; oxidation and scalability challenges	Improved stability via passivation and HF-free synthesis; pilot-scale production	Standardized, biocompatible MXenes integrated in wearable and implantable sensors
Aptamers	Established biorecognition elements in PoC sensors	Expanded clinical validation; multiplexed aptasensing platforms	Routine use in personalized and decentralized diagnostics
MNPs	Signal amplification and separation in lab systems	Better integration with microfluidics and 2DM	Robust hybrid platforms for automated diagnostics
Electrodes	Miniaturized research-grade electrodes	Reproducible, flexible electrodes for wearables	Long-term stable electrodes for continuous monitoring
Channels	Simple microfluidic channels in prototypes	Integrated microfluidics for sample handling and multiplexing	Fully automated lab-on-chip architectures
Inks	Early printable graphene/MXene inks; stability limits	Optimized inks for reproducible printing and flexibility	Commercially available bio-safe inks for large-scale manufacturing
TENGs	Demonstrated self-powered sensing concepts	Improved efficiency and durability for wearables	Integrated energy-harvesting modules in autonomous sensors

better batch control are expected to enable the fabrication of more reliable components, particularly, flexible electrodes and printable inks. This period is characterized by the emergence of multiplexed PoC diagnostics and early clinical pilot studies in wearable electrophysiology applications. In parallel, AI-based tools will mature from exploratory use to semi-standardized workflows that actively guide material synthesis, sensor design, and signal processing, improving performance and reducing development time.

By 2030, the roadmap foresees the convergence of standardized 2DM, manufacturable components, and intelligent data processing into clinically and industrially relevant biomedical sensing platforms. Industrial-scale production of GRM-based materials and stabilized MXenes is expected to support long-term, biocompatible, wearable, and implantable sensors. Applications will shift from ad hoc testing to continuous, personalized monitoring, supported by integrated energy harvesting and embedded AI hardware. At this stage, foundation models and edge-AI chips enable closed-loop optimization, real-time decision support, and predictive diagnostics, positioning 2DM-based sensors as core elements of future smart healthcare systems.

Table 8. 2025–2030 roadmap for materials, components, and biomedical applications (biomedical applications and AI).

	2025	2027	2030
PoC Diagnostics	Single-analyte devices; limited clinical testing	Multiplexed PoC systems entering pilot clinical use	Widely deployed decentralized diagnostics platforms
EMG	Research prototypes with improved comfort	Early commercial wearable EMG patches	Standard components in rehabilitation and prosthetics
ECG	Early 2D-material electrodes in wearables	Improved long-term stability and signal quality	Broad adoption in continuous cardiac monitoring
BCI	Preclinical and early clinical research devices	Pilot clinical systems with improved biocompatibility	Specialized clinical BCIs with multimodal sensing
ML for new materials	Exploratory models for property prediction	Semi-standardized workflows guiding synthesis	Foundation models accelerating materials discovery
DL for new biosensors	Signal denoising and design optimization in labs	Integrated design–test loops for sensor development	Closed-loop autonomous sensor design
AI for signal processing	Post-processing and noise reduction	Real-time analytics in wearable devices	Predictive and decision-support diagnostics
AI chips	External accelerators; limited integration	Low-power edge AI chips for wearables	Fully embedded AI hardware in sensing platforms

8. Conclusions

This roadmap outlines the current status, key challenges, and future directions of 2DM-based biomedical sensing, highlighting the unique opportunities offered by such materials to address the unmet needs in healthcare technologies. The exceptional electrical, optical, and mechanical properties of graphene, MXenes, and related low-dimensional materials have enabled sensing concepts that surpass those of conventional platforms in terms of their sensitivity, flexibility, and integration potential. Simultaneously, the analysis presented in this manuscript demonstrates that scientific maturity alone is insufficient to guarantee translation into real-world biomedical applications.

The central conclusion of this roadmap is that progress over the coming years will depend on coordinated advances across multiple value chain levels. Material synthesis must move toward standardized, reproducible, and scalable processes, whereas biointerface engineering and surface functionalization must ensure long-term stability and selectivity in complex biological environments and meet demanding shelf-life requirements. In parallel, the sensor components and system architectures must be designed with manufacturability, reliability, and regulatory compatibility. Addressing these challenges collectively, rather than in isolation, is essential to bridge the persistent gap between laboratory demonstrations and deployable biomedical sensing systems.

Furthermore, AI is expected to play a growing role as an enabling technology that accelerates material discovery, optimizes sensor designs, and enhances signal interpretation. The integration of AI-driven workflows with 2DM-based sensors is expected to shift biomedical sensing from reactive measurements to predictive and personalized healthcare solutions. Combined with advances in flexible electronics, energy harvesting, AM, and embedded computing, this convergence has created a pathway toward autonomous, continuous, and decentralized diagnostics at scale.

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Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

Conflict of interest

The authors declare that no competing interests exist.

Ethical compliance

No human participants were included in this study besides the authors.

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