



Wearable sensors for health monitoring: Current applications, trends, and future directions



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ABSTRACT

Wearable sensors are redefining health, wellness, and performance monitoring by enabling continuous, non-invasive measurement of biochemical and biophysical signals directly on the body. In this review, we focus on two major classes of wearable technologies: **wearable biochemical biosensors**, including sweat, tear, saliva, and epidermal-based biochemical sensing, and **wearable physical sensors**, which monitor pressure, strain, temperature, motion, and other non-biological signals. We summarize recent advances in materials, microfluidics, and electronics that are enabling more practical and versatile wearable sensing platforms. Particular attention is given to multimodal systems that combine chemical and physical measurements on a single device, on-body fluid handling and sampling strategies, and data processing with embedded algorithms. Commercial examples such as continuous glucose monitors, smart patches, and consumer wearables are also highlighted. Key challenges include getting enough biofluid in a reliable way, reducing signal drift and biofouling, dealing with user-to-user variability, keeping data secure, making sensors comfortable to wear, and setting clear on-body or clinical validation protocols. We also highlight recent efforts that aim to address these issues through better surface coatings, more stable sensor designs, new power and energy-harvesting options, and improvements in data management and manufacturing. This review mainly covers studies published between 2018 and 2025, with a particular focus on work from the last 4–5 years.

1. Introduction

Wearable sensors are integrated analytical platforms that merge point-of-care functionality with mobile connectivity, delivering autonomous, self-contained operation. Wearable sensors are small, lightweight, and flexible devices that have emerged as promising tools for monitoring diverse physiological, biochemical, and environmental parameters directly from the human body (Linh et al., 2025). In particular, wearable sensors enable non-invasive, real-time, and continuous tracking of biological markers, offering valuable insights into human health and performance. These sensors are designed to analyze body fluids such as sweat, saliva, and tears offering valuable health-related information in a non-invasive manner and eliminating the need for

conventional laboratory analyses (Z. Wang et al., 2024; Weng et al., 2024). As illustrated in Fig. 1, wearable biosensing platforms can be broadly categorized into five major types based on their sensing targets and mechanisms: sweat-based, saliva-based, tear-based, epidermal, and non-biological physical sensors.

Each of these biofluids offers distinct advantages by enabling non-invasive, accessible, and real-time monitoring of diverse biomarkers, thereby providing valuable insights into human health. For example, sweat contains electrolytes, metabolites and small molecules (e.g., cortisol, urea, tyrosine), while saliva contains hormones, enzymes, antibodies, antimicrobial agents and drugs relevant for stress and therapeutic monitoring. On the other hand, tears correlate with certain salts, enzymes, proteins, and lipids, enabling non-invasive ocular diagnostics

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(Yang and Gao, 2019). In addition to biofluid-based systems, epidermal sensors are ultra-thin, flexible, and skin-conformal devices that continuously monitor physiological or mechanical signals directly from the skin surface, typically applied to areas such as the arm, forehead, chest, or back (Kim et al., 2019). Furthermore, non-biological wearable sensors are designed to monitor physical and physiological parameters without relying on a biological recognition element. They include mechanical sensors for movement and posture monitoring, electrical sensors for detecting physiological signals, and optical sensors in smart devices that measure heart rate and oxygen saturation (Alugubelli et al., 2022; Nigusse et al., 2021; Viciano-Tudela et al., 2022), and thermal sensors in

patches or textiles to track body temperature (Cho et al., 2022). These platforms enable continuous monitoring, making them essential tools for personalized healthcare.

The rapid advancement of wearable sensor technologies has significantly reshaped the landscape of biomedical engineering, digital health, and personalized medicine (Bakri et al., 2024). As healthcare systems worldwide shift from reactive to preventive and proactive models, the demand for real-time, continuous, and non-invasive monitoring tools has grown exponentially (Hazra and Bora, 2025). For example, progress in microfluidic technology has enabled the non-invasive collection of biofluids such as sweat, saliva, and tears.

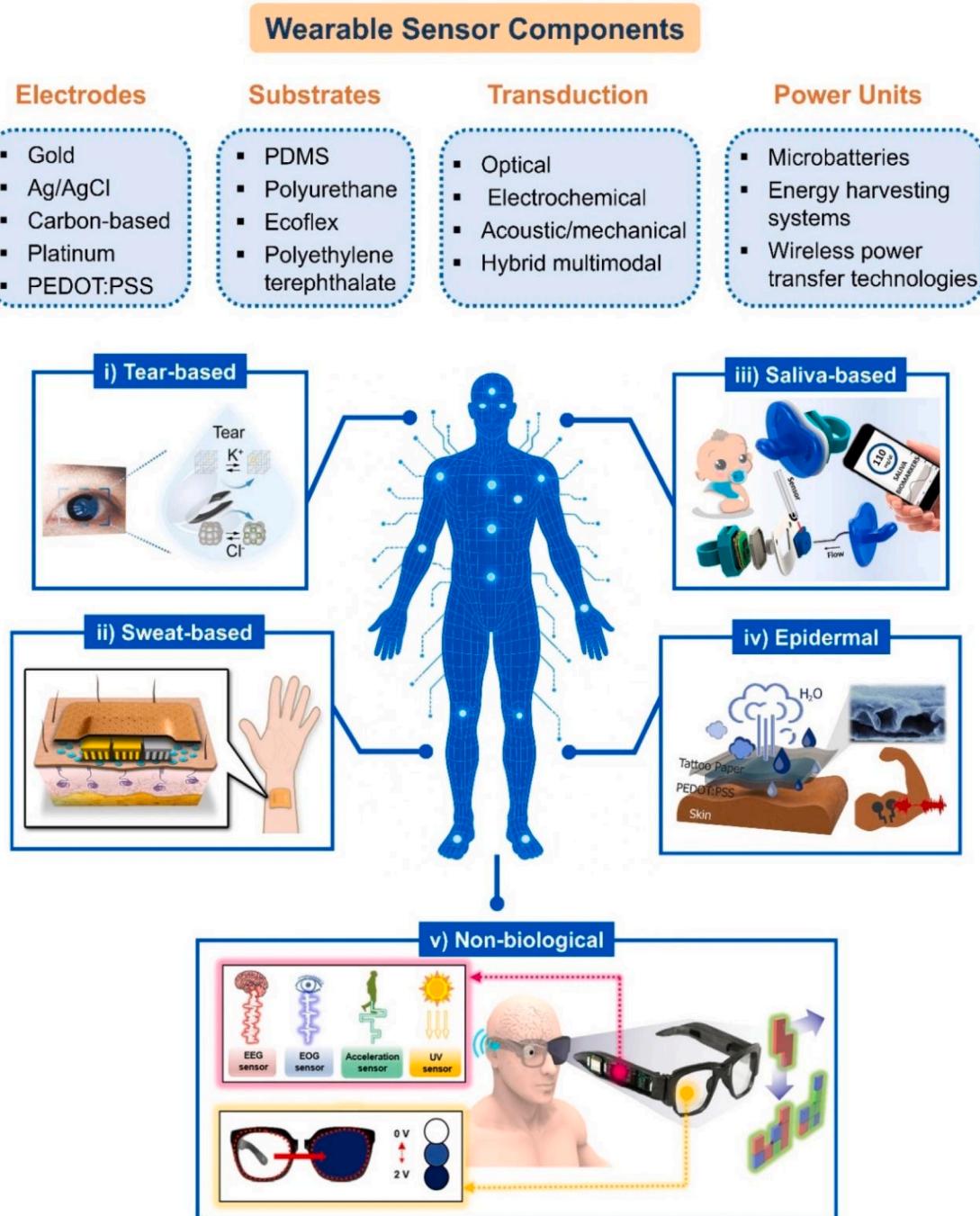


Fig. 1. Schematic illustration of wearable sensor components (top) and representative platforms categorized by sample interface tear, sweat, saliva, epidermal, and non-biological physical sensors (bottom). Panels (i–v) are adapted with permission from (Li et al., 2025; Dervisevic et al., 2022; García-Carmona et al., 2019; Galliani et al., 2025; Lee et al., 2020), respectively.

These systems guide ultra-small volumes (10^{-18} – 10^{-6} L) through micro-to nanoscale channels, where flow rate, pressure, and channel geometry can be precisely controlled to achieve mixing, separation, and flow regulation (Ramachandran and Liao, 2022). Furthermore, nanomaterials have been developed to improve the sensitivity, detection limit, and selectivity properties of wearable sensor platforms (Pimpilova, 2024). Additionally, nanomaterials improve sensor performance by increasing the effective electrode surface for enzyme immobilization and protecting the biorecognition layer from degradation and mechanical stress caused by skin contact (Jamshidnejad-Tosaramandani et al., 2025). Moreover, wireless communication (e.g., Bluetooth, BLE, RFID, Wi-Fi) enables real-time health monitoring and remote data access, positioning wearable sensors as key components of next-generation personalized medicine (Z. Xu et al., 2024).

In this review, we explore the potential of wearable electronic platforms for continuous and simultaneous monitoring of multiple biochemical signals from biofluids, together with key physical parameters such as pressure, motion, temperature, and strain. To clearly position this review within the existing literature, we briefly outline how it complements previous work on wearable devices for sweat, tear, saliva, epidermal, and wearable physical sensors. Earlier literature has often focused on specific biofluids or individual sensing modalities. This review adopts a unified, comparative framework spanning multiple biofluids (sweat, tear, saliva, and epidermal) together with non-biochemical physical wearables, highlighting how these modalities increasingly converge into multimodal platforms. We highlight recent advances and key challenges in developing hybrid biofluid-interfaced devices, focusing on biofluid sampling, transduction mechanisms, and signal integration. We further discuss how wearable bioelectronics, advanced materials, and wireless data processing have enabled miniaturized multimodal sensors, and we review commercially available systems—such as continuous glucose monitors (Abbott FreeStyle Libre, Dexcom G7), smart patches, and multifunctional smartwatches—that illustrate the successful translation of laboratory concepts into real-world healthcare solutions.

2. Wearable sensors in health, wellness, and performance monitoring

Wearable sensors have become essential tools in modern healthcare, wellness, and performance monitoring by enabling continuous and non-invasive measurement of physiological and biochemical parameters directly from the human body. In healthcare applications, they provide real-time tracking of vital signs such as heart rate, blood pressure, body temperature, and oxygen saturation, allowing early diagnosis, personalized treatment, and effective management of chronic diseases. In wellness monitoring, wearable sensors help users maintain a healthy lifestyle by analyzing daily activity, sleep quality, stress levels, and hydration status, offering personalized feedback and behavioral recommendations through integrated mobile or cloud-based platforms. In sports and performance contexts, advanced wearable systems evaluate physical exertion, muscle activity, oxygen uptake, and sweat biomarkers to optimize training efficiency, prevent injuries, and accelerate recovery. The latest generation of wearable devices combines biophysical and biochemical sensing elements on flexible, skin-conformal substrates integrated with wireless connectivity modules for data transmission and real-time analysis. These advances are paving the way for intelligent, multimodal platforms capable of simultaneously assessing multiple health indicators, supporting remote healthcare, telemedicine, and continuous wellness management.

In this review, wearable sensing technologies are categorized under five main categories to emphasize their diverse biofluid interfaces and detection principles. These include wearable biochemical biosensors such as sweat, tear, saliva, and epidermal-based biochemical sensors as well as wearable physical sensors for pressure, strain, temperature, motion, and other non-biological signals. For instance, tear-based

sensors enable non-invasive glucose or electrolyte analysis through smart contact lenses; sweat-based systems allow real-time detection of metabolites such as lactate, cortisol, and sodium during physical activity; and saliva-based sensors provide an accessible route for detecting hormones, pathogens, and biomarkers related to oral and systemic health. On the other hand, epidermal sensors adhere directly to the skin for continuous tracking of physiological signals such as temperature and hydration levels. Lastly, non-biological physical biosensors measure many parameters such as motion, pressure, or strain, which are essential for evaluating body dynamics and performance. By focusing on these categories, this review article highlights the recent technological advances, material innovations, and integration strategies that enable multimodal, skin-conformal, and biofluid-interfaced wearable platforms for comprehensive health and performance monitoring.

2.1. Tear-based wearable sensors

In recent years, human tear fluid has gained increasing attention as a promising biofluid for noninvasive health monitoring. The tear film forms a thin, dynamic layer over the ocular surface, providing lubrication and protection while carrying rich biochemical information that reflects both ocular and systemic conditions (Rajan et al., 2024). Although tears are less complex than blood, it provides an important source of diagnostic biomarkers such as proteins, peptides, amino acids, lipids, glucose, and electrolytes (Moreddu et al., 2019). The biochemical composition of tear fluid dynamically mirrors various physiological states, reflecting changes related to infection, hydration, and overall systemic health. For example, elevated levels of vitamin C have been reported in patients with early-stage corneal injury (Moreddu et al., 2020), while increased concentrations of Ca^{2+} are frequently observed in individuals suffering from dry eye disease (Yetisen et al., 2017). Moreover, alterations in tear protein composition and pH have been associated with ocular pathologies such as aniridia and rosacea.

Tear-based sensors have gained attention for their non-invasive sampling, continuous monitoring capability, and biomarker-rich composition. Different transduction mechanisms mainly electrochemical, fluorescence, photonic crystal, and colorimetric have been employed to convert biochemical interactions into measurable signals (Li et al., 2022). Among these, electrochemical platforms stand out for their high sensitivity, miniaturization compatibility, and low-cost instrumentation, making them strong candidates for non-invasive, real-time tear monitoring in clinical and personalized healthcare.

Fluorescence-based sensors have emerged as another powerful approach for achieving higher sensitivity and molecular specificity in tear biomarker detection. The performance of these sensors generally depends on the structural design and surface chemistry of the employed nanomaterials. The fluorescence response, which correlates with analyte concentration, can originate either from fluorophore-conjugated sensing matrices or from the intrinsic photoluminescent properties of the sensor materials. Among the diverse luminescent nanomaterials, carbon-based structures, especially carbon quantum dots, have garnered significant attention due to their tunable emission spectra, high quantum yield, chemical robustness, biocompatibility, and minimal cytotoxicity. Functionalization of these carbon nanostructures as fluorescent probes has been shown to enhance analyte binding efficiency and substantially improve the detection sensitivity of fluorescence-based tear sensors (Santonocito et al., 2022).

Photonic crystals, periodic refractive-index structures, create photonic band gaps that control light, enabling label-free tear biomarker sensing. They are particularly well-suited for point-of-care tear sensors, offering broad visual detection capabilities due to their unique optical (Chen et al., 2017). These materials feature a periodic dielectric structure that selectively modulates electromagnetic waves at specific frequencies in accordance with Bragg's law (Chen et al., 2018). Beyond photonic crystals, colorimetric sensors also support tear-based detection by producing easy-to-read visual signals through chromogenic

reactions, rather than electrochemical measurements. When coupled with smartphone-based interfaces, these systems provide rapid, low-cost, and portable on-site analysis with real-time digital readout. Building on advances in optical and colorimetric sensing, recent work increasingly aims to translate these principles into wearable platforms for continuous, noninvasive monitoring. For instance, a low-cost, noninvasive contact lens-based glucose sensor was reported, in which the lens surface is functionalized with boronic acid via a poly(tannic acid) coating to reversibly bind glucose in tears. After release into an enzymatic cocktail, glucose is quantified by colorimetric readout on a smartphone and by UV-Vis analysis, while the lens maintains transparency, oxygen permeability, and biocompatibility. In another study, microfluidic tear sampling was combined with smartphone-read colorimetry to create an affordable wearable platform that quantifies tear biomarkers using smartphone imaging with Machine Learning (ML)-based color correction. This system integrates simple chemistry, controlled fluid handling, and an end-to-end image pipeline, and demonstrates performance in tear-relevant ranges, outlining a path toward standardized, real-world deployment (Seo et al., 2024).

Based on their operational mode, wearable tear sensors are generally categorized into four main types: strip-based platforms, contact lens-integrated sensors, spring-like wearable devices, and eyeglass-mounted biosensing systems (Yu et al., 2019). Electrochemical tear sensors generally operate through enzyme-mediated oxidation (for example, glucose oxidase for glucose), in which the enzymatic reaction generates electroactive species that modulate the current at a working electrode. Potentiometric platforms employ ion-selective membranes and transduce analyte-ion interactions into changes in electrochemical potential across the membrane. Optical and fluorescent tear sensors typically rely on analyte-induced changes in emission intensity, photoluminescence quenching, or refractive index modulation in photonic structures. In parallel, microfluidic tear collectors exploit capillary-driven flow and carefully engineered microchannel geometries to transport ultra-small tear volumes to the sensing region while minimizing evaporation and sample loss.

Early wearable tear sensors were primarily designed as strip-based platforms. For example, Lin et al. developed a lactate biosensor employing a protein-engineered lactate oxidase to achieve oxygen-independent detection, integrated onto a screen-printed electrode for efficient tear sampling. This biosensor exhibited a linear detection range of 0.39–16.60 mM in artificial tear fluid, and demonstrated high selectivity against common tear interferents such as ascorbic acid, acetaminophen, and uric acid, and maintaining stability over eight weeks of storage (Lin et al., 2018). Although strip-based sensors have been used for various diagnostics, they typically offer poor integration between sensing and data processing. Their stable placement on the eye is difficult, and the rigidity of plastic substrates can cause discomfort and reflex tearing, limiting their suitability for continuous wearable use. To address these limitations, subsequent research has focused on contact lens-integrated systems capable of real-time monitoring of tear biomarkers through direct ocular contact. These platforms offer improved comfort, biocompatibility, and stability. Mukundan et al. developed a flexible and non-invasive contact lens sensor incorporating a nickel–cobalt metal–organic framework hydrogel for urea detection in tear samples. This sensor exhibited a detection limit of 0.445 mM and a linear response range of 0.5–70 mM, demonstrating high selectivity toward common interferents. Enhanced urea oxidation arose from Ni–Co synergy, and the binder-free, non-toxic platform enabled stable, continuous sensing in simulated tear media (Mukundan and Badhulika, 2024).

Spring-like wearable tear sensors have also been introduced as innovative platforms designed to conform around the eye contour, enabling stable and continuous tear analysis with minimal interference to natural ocular functions. For example, the NovioSense glucose sensor allows continuous monitoring of glucose levels in basal tear fluid, demonstrating a strong correlation with blood glucose concentrations.

Flexible coiled electrodes encapsulated in a GOx hydrogel oxidize glucose to H₂O₂, yielding a chronoamperometric signal. The coil sits comfortably under the lower eyelid, and wireless transmission enables real-time monitoring with sub-mM detection limits and interference tolerance (Kownacka et al., 2018).

Eyeglass-mounted sensors extend tear-based wearables by embedding analytical modules into everyday eyewear for unobtrusive monitoring. A microfluidic nose-pad electrochemical platform has been demonstrated for real-time tear biomarker analysis. Using an alcohol oxidase-based sensor positioned outside the eye, it enables direct alcohol detection in stimulated tears without contact lens-related limitations. Frame-integrated wireless electronics create a compact eyeglass system that correlates well with blood alcohol levels and can also monitor tear glucose and vitamin levels (Sempionatto et al., 2019).

These advances show how wearable tear sensors are diversifying to balance comfort, stability, and analytical precision. Contact lens-integrated and microfluidic designs now lead the field by pairing direct ocular access with precise fluid handling. In particular, microfluidic platforms use miniaturized channels for controlled sampling, low reagent consumption, and high analytical performance well suited to point-of-care use (Park et al., 2025). Representative configurations of these wearable tear sensors are summarized in Fig. 2.

Recent studies on contact lens-based sensors have focused on developing smart lenses that can both monitor ocular biomarkers and deliver targeted therapy. Keum et al. developed smart contact lenses for simultaneous glucose monitoring and treatment of diabetic retinopathy. These contact lenses, fabricated on a biocompatible polymer, incorporate ultrathin flexible circuits and an integrated microcontroller, enabling real-time electrochemical sensing, wireless power transfer, and controlled drug release, as shown in Fig. 2A. In diabetic rabbits, lens-measured tear glucose tracked blood glucose, and on-lens drug release aided retinal therapy supporting smart lenses as noninvasive diagnostic–therapeutic platform (Keum et al., 2020).

Beyond electrochemical sensing and drug delivery, optical strategies have also been introduced to broaden the analytical scope of contact lens sensors. In particular, as illustrated in Fig. 2B, the smart theranostic contact lens incorporates a highly sensitive intraocular pressure sensor based on gold hollow nanowires (AuHNW), a flexible drug-delivery system, an application-specific integrated circuit (ASIC) chip. This system enables both continuous intraocular pressure (IOP) monitoring and on-demand therapeutic intervention. In vivo experiments performed in glaucoma-induced rabbits further validated this multifunctional platform, demonstrating reliable real-time intraocular pressure measurement and effective pressure reduction through controlled timolol release (T. Y. Kim et al., 2022).

Nanomaterial-based lenses have recently emerged for label-free and highly sensitive glucose detection. In the study illustrated in Fig. 2C, a biocompatible nanoparticle-incorporated contact lens containing GOx and cerium (III) oxide was developed for noninvasive glucose monitoring. The device displayed distinct spectral responses in reflection corresponding to varying glucose concentrations, enabling the generation of a calibration relationship. In diabetic mouse experiments, the glucose levels detected in tears with the optical contact lens sensor were in good agreement with those in blood (Kim et al., 2020).

Building on these optical approaches, efforts have also turned toward integrating microfluidic components and artificial intelligence to achieve real-time, multianalyte tear analysis. Accordingly, Wang et al. introduced a wearable microfluidic colorimetric sensor enhanced with artificial intelligence for rapid, non-invasive, and simultaneous measurement of key tear biomarkers, including vitamin C, pH, Ca²⁺, and proteins as shown in Fig. 2D. This sensor integrates a flexible microfluidic patch for tear collection and colorimetric detection with a smartphone-based deep-learning framework for data acquisition, processing, and visualization. A multichannel convolutional recurrent neural network is employed to compensate for variations in pH and illumination, thereby enhancing the accuracy and reliability of

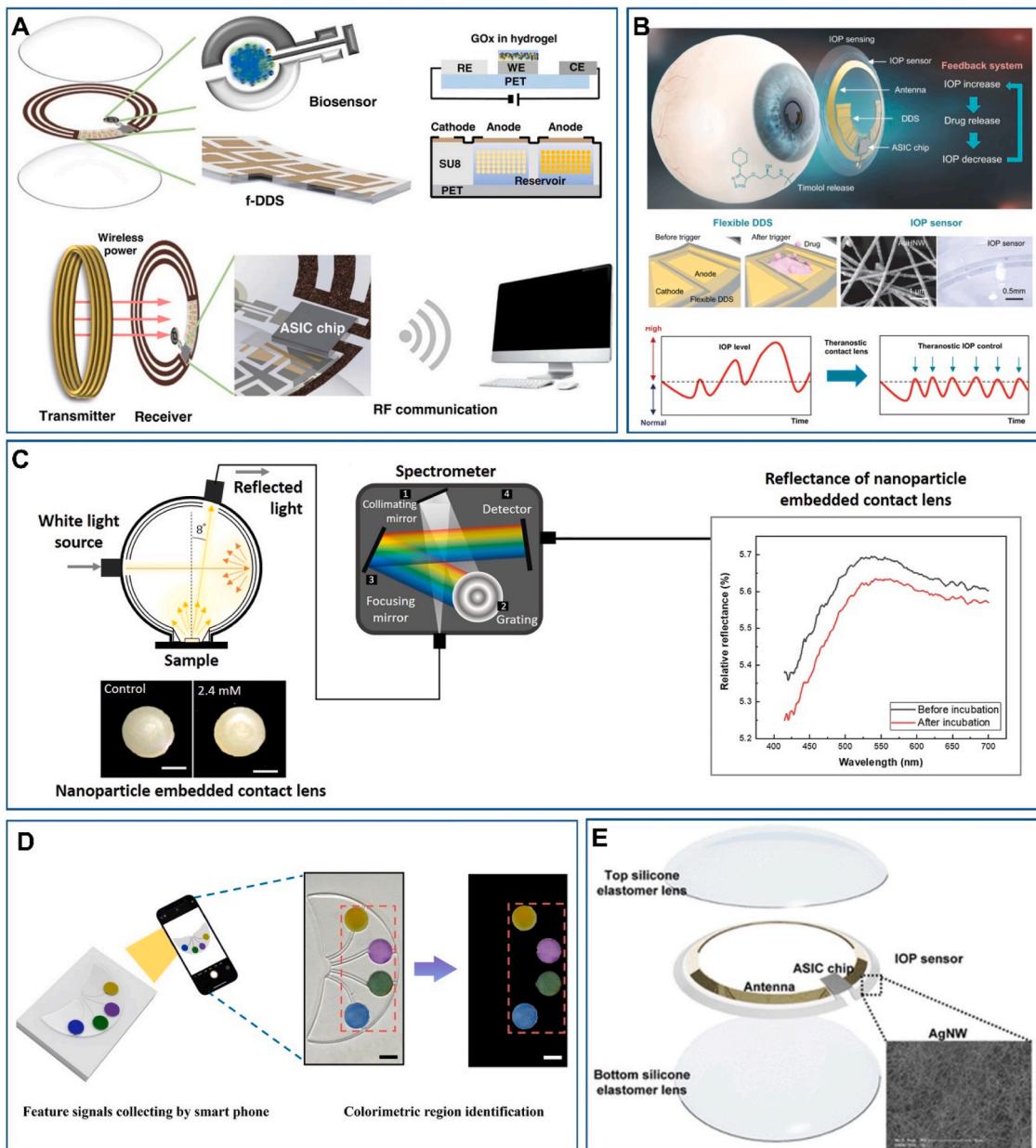


Fig. 2. Tear-based wearable sensors: A) Smart contact lens for electrochemical glucose monitoring and drug delivery (Keum et al., 2020). B) Smart contact lens for continuous IOP monitoring and on-demand timolol release (T. Y. Kim et al., 2022). C) Nanoparticle-embedded contact lens for optical glucose sensing (Kim et al., 2020). D) Microfluidic colorimetric platform with AI-assisted analysis for multianalyte tear detection (Z. Wang et al., 2024). E) Wireless smart contact lens with transparent Ag nanowire strain sensor for continuous intraocular pressure monitoring (Kim et al., 2021). All images adapted with permission from the respective publishers.

biomarker quantification (Z. Wang et al., 2024).

While most tear sensors target biochemical markers, mechanical parameters such as intraocular pressure are equally critical for ocular diagnostics. In Fig. 2E, a wireless smart contact lens integrating a transparent silver nanowire strain sensor was engineered for noninvasive, continuous monitoring of intraocular pressure. The device maintained stable performance under simulated tear conditions and throughout repeated eyelid blinking cycles, demonstrating robustness for practical ocular applications. Sensor functionality was validated both *in vitro* using polydimethylsiloxane (PDMS) eye models and *in vivo* in rabbit eyes, with intraocular pressure measurements showing strong concordance with conventional invasive tonometry (Kim et al., 2021). Following these advancements, a transparent and stretchable multi-functional contact lens sensor capable of wirelessly monitoring both tear

glucose and intraocular pressure was introduced. The device utilized a graphene–silver nanowire hybrid network to provide high conductivity, transparency, and mechanical flexibility. GOx was immobilized on the graphene channel for selective glucose detection, while intraocular pressure changes were tracked via variations in capacitance and inductance. The sensor achieved a low glucose detection limit of 0.4 mM, demonstrated reliable wireless operation *in vivo* on a rabbit eye, and exhibited linear intraocular pressure responses within the physiological range (Kim et al., 2017). In another approach, a smart contact lens was developed incorporating bimetallic Au@Pt nanocatalysts embedded within a nanoporous hydrogel matrix for noninvasive glucose monitoring. The nanocatalysts enhanced charge transfer and catalytic efficiency, enabling rapid and sensitive electrochemical detection, while the hydrogel ensured stable diffusion and sustained sensor performance.

In vivo evaluations demonstrated a strong correlation between tear and blood glucose levels (S. Kim et al., 2022).

In addition, a wearable contact lens sensor was designed for noninvasive tear glucose monitoring using cerium oxide nanoparticles conjugated with GOx via poly(ethylene glycol). Glucose oxidation induced a rapid Ce³⁺ to Ce⁴⁺ color change, which was quantified using a smartphone-based image analysis algorithm. The system achieved a detection limit of 0.1 mM, demonstrated biocompatibility, and reliably measured tear glucose in diabetic rabbits and human specimens, effectively differentiating diabetic from healthy individuals (Park et al., 2021). Beyond glucose monitoring, wearable tear sensors have also been adapted for the detection of other clinically relevant biomarkers such as creatinine. Serum creatinine serves as a vital biochemical indicator for assessing renal function and glomerular filtration rate. In this context, a fiber-integrated eyeglass platform was developed for noninvasive tear creatinine monitoring, constructed from a copper-benzenedicarboxylate (metal-organic framework (MOF) coupled with graphene oxide–Cu(II) and Cu₂O nanoparticles. Density functional theory calculations and EIS characterization confirmed strong coordination between creatinine and copper centers, along with enhanced charge-transfer efficiency. The system achieved over 95 % selectivity across 1.6–2400 μM and 83.3 % accuracy in machine-learning-based classification of creatinine levels (Kalasin et al., 2021).

Wearable microfluidic platforms also enable simultaneous monitoring of multiple tear biomarkers. For instance, wearable microfluidic contact lenses were developed for real-time detection of tear pH, glucose, proteins, and nitrite ions. CO₂ laser-patterned microchannels incorporated biosensors at the ends of four branches extending from a central ring, and colorimetric responses were processed via a smartphone-MATLAB nearest-neighbour algorithm. The sensors responded within 15 s, exhibiting sensitivities of 12.23 nm/pH, 1.4 nm/mmol L⁻¹ for glucose, 0.49 nm/g L⁻¹ for proteins, and 0.03 nm/μmol L⁻¹ for nitrites (Moreddu et al., 2020). Extending these microfluidic strategies to targeted biomarkers, researchers have also developed sensors for ascorbic acid, a key indicator of ocular inflammation. Shi et al., engineered a fluorescent contact lens for in situ monitoring of tear fluidic strategies to targeted biomarkers sensors for ascorbic acid using BSA–Au nanoclusters (NCs) as the sensing probe. The NCs were synthesized and encapsulated within a poly(vinyl alcohol) and citric acid matrix, integrated into a laser-ablated microfluidic region of the lens. Tear fluid flowing through the microchannel enabled real-time fluorescence measurements, which were quantified via a smartphone-based imaging platform. The sensor achieved a detection limit of 0.178 mmol L⁻¹ and demonstrated stable performance over a 20-h operational period with 10-day storage stability (Shi et al., 2024).

In summary, tear-based wearable sensors typically rely on contact lenses, microfluidic eye patches, or periocular flexible platforms. Their main strengths include the rich biochemical content of tears and the close physiological correlation with systemic biomarkers such as glucose, electrolytes, and stress indicators. Despite recent milestones, tear-based wearables remain constrained by limited tear volume, making continuous sampling and stable signal generation difficult. In addition, tear secretion can vary significantly depending on emotional state, environmental conditions, and eye health, leading to inconsistent analyte concentrations. Tear stimulants can distort native tear chemistry and bias readings. Ensuring ocular biocompatibility and comfort is critical, as prolonged lens/sensor contact may irritate or disrupt tear-film dynamics; contamination (makeup, dust, blinking) can further impair signals. Key challenges for practical use include long-term stability, miniaturized power/communications, and robust tear-blood biomarker correlations.

2.2. Sweat-based wearable sensors

Sweat, produced by eccrine glands (secretory coil with a dermal duct), is a rich biofluid for non-invasive, continuous, real-time

monitoring containing electrolytes (Na⁺, K⁺, Cl⁻), metabolites, and hormones. The biochemical composition of sweat reflects its dynamic exchange with blood and interstitial fluid, where analyte partitioning depends on factors such as molecular size, charge, and pH (Xu et al., 2021). Wearable sweat sensors must deliver fresh sweat rapidly and co-measure key ions (Na⁺, K⁺) to correct for sweat-rate effects. Microfluidic isolation layers limit evaporation and contamination, while engineered interfaces suppress long-term drift. Ultimately, reliability hinges on consistent sampling and proper calibration, now commonly achieved with microfluidic flow paths and active sweat induction, which has become standard practice. Fig. 3 shows representative sweat-based wearable sensors.

Most sweat wearables employ enzymatic amperometric transduction, where oxidase enzymes (such as glucose oxidase or lactate oxidase) convert target metabolites into electroactive species and the resulting faradaic currents scale with analyte concentration. Potentiometric ion sensors use ion-selective membranes and solid-contact electrodes to provide Nernstian responses to Na⁺, K⁺, and pH, enabling electrolyte and hydration assessment. Impedance- and conductance-based devices track changes in charge-transfer resistance and double-layer capacitance at the electrode–sweat interface, which reflect local ionic strength and biofouling. Iontophoresis-enabled systems integrate controlled electrical stimulation to induce sweat production on demand, while microfluidic channels regulate sweat transport, reduce evaporation, and isolate freshly produced sweat from the skin surface to stabilize the analytical readout.

Iontophoresis, one of the earliest reported methods, employs electrical stimulation to drive transdermal delivery. In this method, cholinergic drugs (pilocarpine and carbachol) are applied to the skin, where they enter the eccrine glands and stimulate sweat production (Legner et al., 2019). Early field systems integrated pilocarpine iontophoresis and macroparticle collection with portable solid-state ion-sensitive electrodes (ISEs) arrays, enabling simultaneous Na⁺/K⁺/Cl⁻ measurements (Lynch et al., 2000). These early demonstrations led to skin-mounted microfluidic modules that reduced leakage and evaporation while improving temporal resolution. Building on this, fully integrated programmable iontophoretic interfaces were developed that apply periodic, safety-limited stimulation and multiplex on-skin Na⁺/Cl⁻/glucose sensing. By directly coupling controlled stimulation with electrochemical readout, these systems enable cystic fibrosis screening and glucose monitoring (Emaminejad et al., 2017).

Further optimization introduced iontophoretic patches combining membrane isolation, sudomotor axon-reflex stimulation and a rapid "hex-wick" interface with an alcohol oxidase (AOx) amperometric sensor ensures complete wetting while reducing contamination. This configuration maintains correlations between sweat and blood ethanol concentrations and enables the quantification of detection time (Kim et al., 2016). However, standard iontophoresis can lead to electrode corrosion and skin irritation. In contrast, programmable current designs enable controlled sweat induction by regulating ion electroosmotic flow, greatly reducing overheating and burn risk (Gao et al., 2023).

Microfluidic sweat collection has progressed from passive, evaporation-resistant patches to actively perfused architectures that decouple analyte readout from native sweat rate. In the initial design (Fig. 3A), a paper-based 3D microfluidic patch with hydrophilic/hydrophobic patterning and waxed-thread channels programs flow timing, sequentially routing fresh sweat to electrochemical and colorimetric zones. This configuration multiplexes glucose, lactate, uric acid, Mg²⁺, and pH colorimetry with electropolymerized e-MIP cortisol sensing on a Prussian blue transducer, while minimizing backflow and evaporation. (Cheng et al., 2023).

The passive and evaporation-resistant sampling method is further developed (Fig. 3B) which demonstrates measurements that are structurally independent of native sweat rate using an actively perfused wristband/watch (Konno and Kudo, 2024). The concept of an active-transport wristwatch/band involves the imposition of

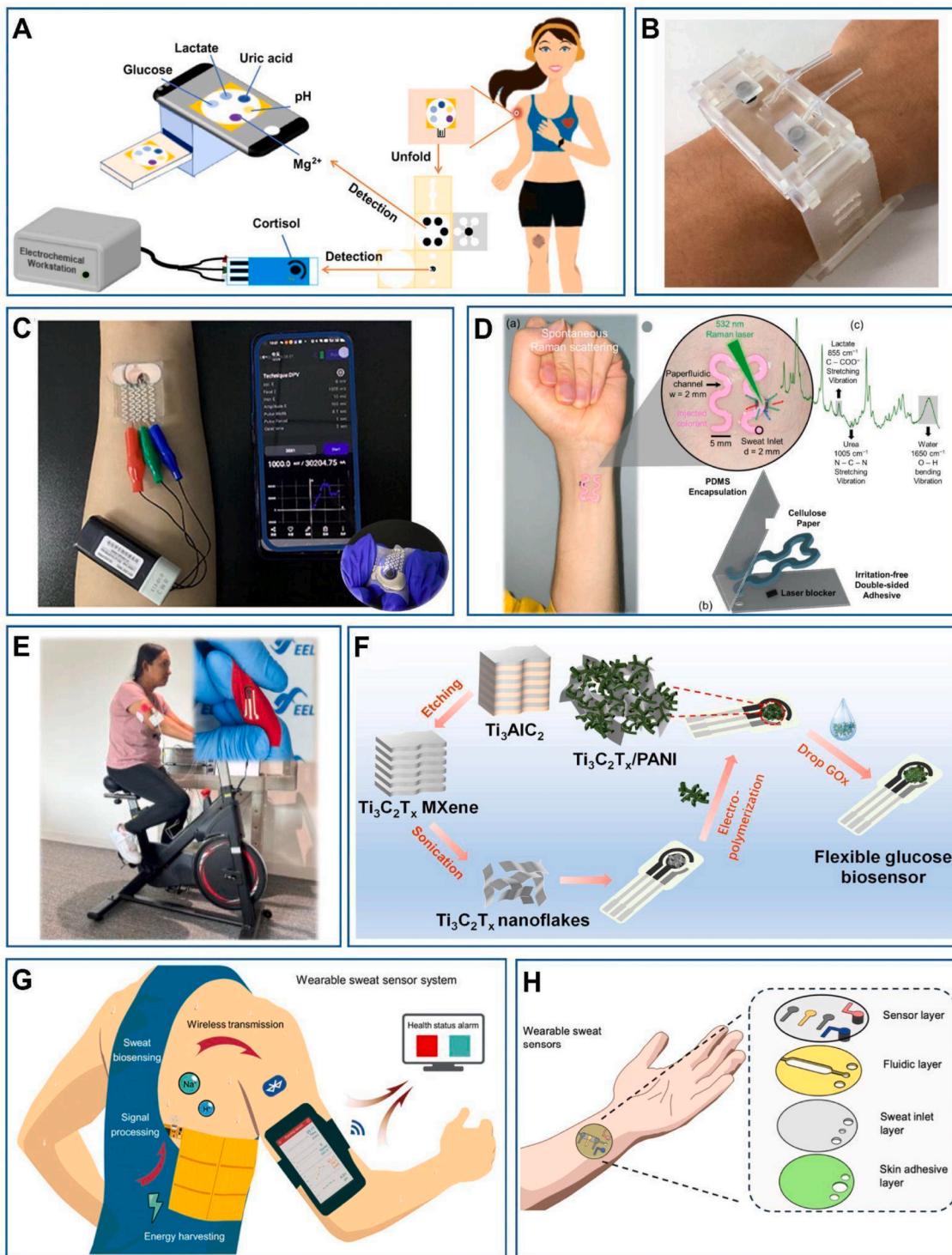


Fig. 3. Sweat-based wearable sensors: **A)** 3D origami paper patch integrating colorimetry and electrochemical cortisol detection (Cheng et al., 2023). **B)** Active-transport band enabling sweat-rate-independent lactate monitoring (Konno and Kudo, 2024). **C)** Electrochemical patch with antifouling, self-healing AuNP/MoS₂/peptide hydrogel (Qiao et al., 2023). **D)** Opto-paperfluidic Raman patch for label-free urea and lactate detection (Golparvar et al., 2023). **E)** Screen-printed textile sensor with Prussian blue-carbon electrodes for glucose sensing (Khosravi et al., 2023). **F)** MXene/PANI enzyme electrode for chronoamperometric glucose detection (J. Wang et al., 2024). **G)** Battery-free triboelectric-powered microfluidic sensor for pH and Na⁺ monitoring (Song et al., 2020). **H)** Integrated systems framework outlining design principles for reliable on-body sweat analytics (Childs et al., 2024). All images adapted with permission from the respective publishers. Sweat wearables commonly employ epidermal patches, microfluidic channels, textiles, or iontophoresis-enabled systems. Their advantages include non-invasive collection, relatively high analyte accessibility, and compatibility with both electrochemical and colorimetric sensing. Passive sweat collection is suitable for high-sweat-rate scenarios, whereas iontophoresis is preferred when controlled or continuous sampling is needed, such as in low-sweat individuals. Major limitations include sweat-rate variability, contamination, evaporation, and calibration drift during prolonged wear. Sweat sensors are among the most mature wearable modalities, but still require improved standardization and on-body stability.

constant-flow phosphate-buffered saline (PBS) perfusion at the skin surface with a view to conveying freshly secreted sweat to a downstream microfluidic electrochemical cell. The sensor quantifies lactate via enzymatic amperometry using lactate oxidase and osmium-wired peroxidase on a screen-printed carbon working electrode with an Ag/AgCl reference. In on-body tests, its response was largely independent of natural sweat rate, enabling real-time tracking of exercise-induced lactate and mitigating the long-standing “sweat-rate bias” of passive or sealed systems. Once microfluidic flow is stabilized, the remaining challenge is signal stability and drift at the sensing interface. To address this, recent designs employ diode-connected extended-gate transistor pairs, which drive a sensing gate (functionalized with an ion-selective membrane or enzyme/aptamer layer) together with a reference gate to cancel common-mode perturbations (e.g., temperature, strain). This architecture enables low-drift monitoring of sweat biomarkers such as cortisol (aptamer-based), glucose (enzymatic), and Na^+ (ion-selective), while the extended-gate layout electrically isolates the semiconductor channel from the biofluid via a solid dielectric, improving robustness against fouling (Zhong and Inal, 2025).

Complementary to circuit stabilization, surface-level antifouling layers have been integrated at the bio-electrode surface. As shown in Fig. 3C, a self-healing, electrically neutral peptide–nanocomposite hydrogel composed of AuNPs/MoS₂/peptide was introduced as an antifouling interlayer to maintain stable electrochemical performance under continuous operation. The oxidation currents of uric acid and ascorbic acid were measured using differential pulse voltammetry (DPV) with the aim of assessing sensing performance and antifouling behavior. In the undiluted sweat, the control electrodes demonstrated substantial DPV signal suppression (approximately 45 %), whereas the D-peptide complex hydrogel preserved the signal with minimal suppression, indicating durable biofouling resistance (Qiao et al., 2023).

In Fig. 3D, an opto-paperfluidic system employed capillary wicking for rapid sweat delivery and ratiometric Raman spectroscopy for urea and lactate quantification under dynamic conditions. This method eliminated the need for plasmonic enhancement or biorecognition coatings, minimizing both reaction-time delays and signal drift, thus advancing the reliability of continuous optical readouts (Golparvar et al., 2023).

Recent studies in materials science have increasingly focused on electrochemical sensor designs, emphasizing wearable configurations and material optimization for improved on-body stability and comfort. For instance; a breathable textile biosensor was screen-printed onto fabric, combining Prussian blue–carbon working/counter electrodes with an Ag/AgCl reference (Fig. 3E). GOx immobilized in a chitosan-single-walled carbon nanotubes/bovine serum albumin matrix beneath a Nafion overcoat enabled low-potential amperometry (-0.1 V) for sweat glucose ($20\text{--}1000\text{ }\mu\text{M}$) with high sensitivity under on-body conditions in a textile microfluidic system (Khosravi et al., 2023).

Further, a coral-like $\text{Ti}_3\text{C}_2\text{T}_{\text{x}}$ MXene/polyaniline (PANI) nanocomposite electrode (Fig. 3F) provided enhanced stability and conductivity, serving as both transduction and enzyme immobilization layer in chronoamperometric glucose sensors (J. Wang et al., 2024). Similarly, the paper-based 3D glucose patch has been developed to achieve low-potential amperometry (0.1 V) with Prussian-blue mediation. The sequential NEXAR/chitosan/GOx/protective layers on screen-printed carbon working/counter electrodes with an Ag reference have been shown to improve selectivity, suppress interferences and enable rapid on-body response under capillary-driven flow (Noura et al., 2022).

To achieve energy independence, a battery-free microfluidic patch (Fig. 3G) coupled flexible printed circuits with a triboelectric nanogenerator, harvesting approximately 416 mW m^{-2} from human-motion to power Bluetooth Low Energy (BLE) telemetry for pH and Na^+ monitoring (Song et al., 2020). Potentiometric transduction employed a PANI pH electrode, a PVC/ Na^+ -ionophore X membrane on a PEDOT: PSS solid contact for Na^+ , and a PVB-coated Ag/AgCl reference, yielding near-Nernstian slopes with strong selectivity and stability.

A recent integrative analysis (Fig. 3H) consolidates these advances into a cohesive systems model (Childs et al., 2024). The framework defines prerequisites for reproducible on-body sweat analytics: auxiliary sensing (pH, temperature, electrolytes), on-patch flow metrology, and robust adhesion/sealing with evaporation control. It also covers sensor placement, sampling strategy, long-duration safe stimulation, and biocompatible materials. Finally, it flags the persistent sweat–blood correlation problem, advocating multimodal normalization and standardized sampling to reduce interferences.

2.3. Saliva-based wearable sensors

Saliva has emerged as a promising diagnostic fluid in modern biomedical research, providing clinically valuable information owing to its non-invasive collection, easy storage and processing, and the presence of multiple biomarkers. It serves as a valuable biomarker for the early detection of both oral and systemic diseases. Its soluble biomarkers provide opportunities not only for disease prognosis and therapeutic monitoring but also for patient management across a wide range of conditions, including cancer, metabolic, neurodegenerative, infectious, and autoimmune disorders. Particularly, its capacity for multiplex biomarker analyses underscores potential in point-of-care devices, rapid diagnostic kits, and centralized clinical laboratory platforms. Fig. 4 illustrates representative examples of intra-oral and saliva-based bio-sensing platforms.

The first wearable intraoral biosensor was reported in 2012 (Mannoor et al., 2012). This pioneering intraoral wearable biosensor targeted selective detection of pathogenic bacteria. A graphene-based microbial nanosensor was bio-transferred onto tooth enamel using water-soluble silk, yielding a wireless, battery-free, biocompatible platform. Graphene functionalized with antimicrobial peptides enabled single-cell bacterial detection by leveraging its large surface area and high conductivity. An integrated readout coil provided wireless power and data transfer, enabling remote monitoring of respiration and salivary microorganisms and demonstrating the feasibility of graphene-based bioelectronics for continuous, non-invasive oral microbial monitoring.

The first non-invasive intraoral metabolite sensor reported in the literature was a mouthguard biosensor developed for lactate monitoring (Kim et al., 2014). However, the initial prototype was not equipped with wireless functionality; consequently, the measurements were conducted within the laboratory setting, employing an electrochemical analyzer with wired electrode connections. Despite this limitation, the device demonstrated high sensitivity, selectivity, and stability, thereby providing the first evidence that the oral cavity could serve as a suitable platform for continuous biochemical monitoring. Further advancement was performed by developing a wireless intraoral mouthguard biosensor for salivary uric acid detection (Kim et al., 2015). This platform integrated a uricase-modified Prussian Blue electrode with miniaturized electronics, including a potentiostat, microcontroller, and BLE transceiver. It facilitated real-time wireless communication with standard consumer electronics and demonstrated high sensitivity, selectivity, and stability for salivary uric acid detection.

Building on this wireless intraoral architecture, continuous oral hygiene monitoring was achieved using a mouthguard-type biosensor (Fig. 4A) incorporating optimized LED wavelength selection and material engineering for high-sensitivity turbidity detection. The device exhibited a broad quantification range ($1\text{--}4000\text{ FTU}$) and demonstrated excellent concordance with spectrophotometric analyses in both *in vitro* and *in vivo* evaluations, confirming its accuracy and robustness for real-time salivary monitoring (Ichikawa et al., 2024).

Expanding beyond mouthguard configurations, a poly(vinylidene fluoride)-cohexafluoropropylene (PVDF-HFP) nanomesh smart face-mask (Fig. 4B) enabled electrochemical cortisol detection with high reproducibility. This nanomesh face-mask employed highly gas-permeable PVDF-HFP nanofiber networks and functionalized

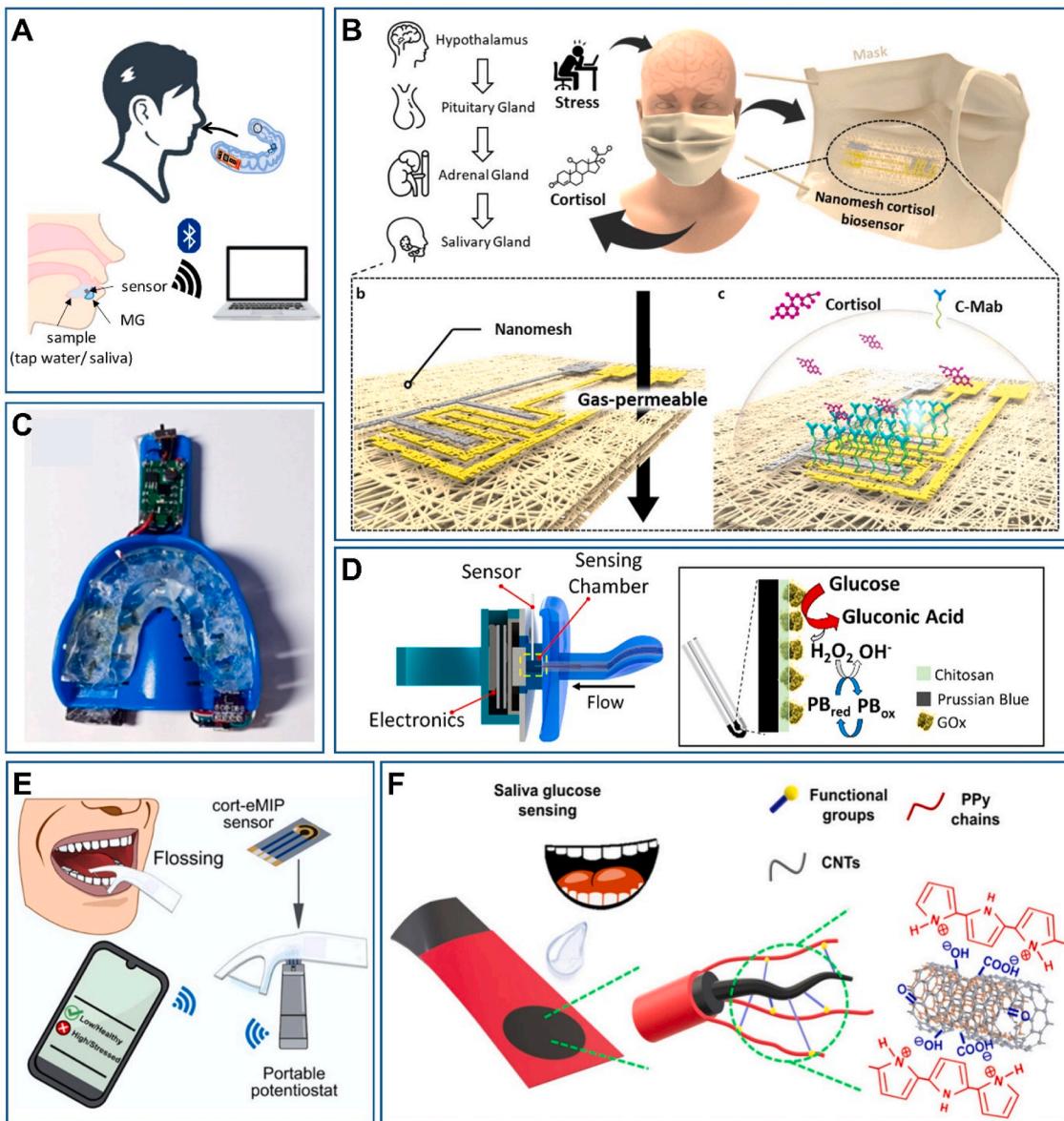


Fig. 4. Representative intra-oral and saliva-based biosensing platforms: A) Schematic of the in vivo wireless salivary turbidity measurement experiment using the mouthguard-type biosensor (Ichikawa et al., 2024). B) PVDF-HFP nanomesh face mask with interdigitated electrodes for salivary cortisol detection (Cho et al., 2025). C) Intra-oral “dental-tray” platform integrating temperature/humidity sensing, a personalized microfluidic module, and a piezo micropump for threshold-triggered dosing (Popović et al., 2023). D) Wireless pacifier that pumps saliva to an external electrochemical chamber for on-body glucose readout correlated with blood glucose (García-Carmona et al., 2019). E) Dental-floss platform that uses thread microfluidics and a cortisol-specific eMIP on porous laser-engraved graphene (Sharma et al., 2025). F) Core-shell PPy/CNT hydrogel on carbon paper for salivary glucose sensing (Liu et al., 2025). All images adapted with permission from the respective publishers.

interdigitated electrodes to enable salivary cortisol measurement, supported by specificity controls and comparisons with clinical samples. Enhancement of surface wettability via oxygen plasma promoted uniform spreading of saliva droplets captured by the mask across the electrodes and improved electroanalytical repeatability (Cho et al., 2025).

Complementing this face-mask modality, an intraoral portable microelectronic device (Fig. 4C) was developed to enable continuous monitoring of oral temperature and humidity, while a micropump was actuated to deliver artificial saliva as needed. The system was designed to automatically dispense artificial saliva through the micropump when preset thresholds were exceeded, for example, when humidity levels dropped below 65 % and oral temperature increased (Popović et al., 2023). Although mouthguard systems successfully demonstrated continuous salivary metabolite monitoring, they were not practical for

infant use. This challenge was addressed in 2019 with the development of a pacifier-based biosensor, as shown in Fig. 4D. This non-invasive infant platform converts natural sucking into unidirectional saliva flow toward an external electrochemical cell, enabling glucose quantification via GOx-modified Prussian Blue electrodes (García-Carmona et al., 2019). By adopting disposable sensing elements, the system mitigates biofouling and supports stable, real-time wireless readout, outperforming prior mouthguard-based designs for infant use. Following this concept, a smart bioelectronic pacifier was developed for real-time monitoring of salivary electrolytes, particularly sodium and potassium levels (Lim et al., 2022). They describe a pacifier-based platform that couples bioelectronic circuitry with wireless readout for continuous, non-invasive monitoring of glucose and electrolytes in infants, demonstrating the feasibility of intraoral biomarker tracking without invasive sampling.

Building on infant-appropriate formats and salivary metabolite monitoring, the next generation developments focused on chronic stress assessment within a user-compliant configuration as illustrated in Fig. 4E. This study integrated floss-based thread microfluidics with MIP-based electroanalytical detection, resulting in the capacity to quantitatively measure salivary cortisol at the point of care within a time frame of 11–12 min (Sharma et al., 2025). The study attained a limit of detection of 0.048 pg mL^{-1} and exhibited a high degree of correlation with ELISA ($r = 0.9910$).

In the context of diabetes management, a salivary glucose biosensor employing a core-shell polypyrrole (PPy)/carbon nanotube (CNT) architecture was developed (Fig. 4F), using three-dimensional, interconnected conducting-polymer hydrogel/carbon-nanotube networks (Liu et al., 2025). This study provided methodological advances by enabling *in situ* hydrogel formation of cross-linked PPy on CNT surfaces via electrostatic interactions and by introducing morphology-controlled strategies for enzymatic sensor design.

Intraoral and saliva-based wearable sensors mainly use amperometric and potentiometric electrochemical transduction, where enzymes (e.g., glucose oxidase, uricase, lactate oxidase) or ion-selective membranes convert salivary analytes into electrical signals. Saliva is typically routed to these sensing interfaces via simple microfluidic structures and capillary flow, while optical platforms detect analytes through colorimetric or fluorescence changes on nanostructured surfaces. Saliva-based platforms often use mouthguards, intraoral patches, chewing-gum-inspired sensors, or mask-integrated microfluidic systems. Saliva provides high analyte richness and strong diagnostic relevance; however, issues such as viscosity, enzymatic activity, mucins, and biofouling can complicate reliable sensing. Optical or electrochemical readouts benefit from antifouling coatings and controlled microfluidic routing to enhance stability. While intraoral systems offer excellent biochemical access, long-term wearability, user comfort, and mechanical robustness remain the primary engineering challenges.

2.4. Epidermal sensors

Epidermal sensors are ultra-thin, flexible, and skin-conformal devices designed to continuously monitor physiological, biochemical, or mechanical signals directly from the surface of the skin. These sensors adhere seamlessly to the epidermis, providing stable and comfortable long-term measurements. They can be constructed from soft, stretchable and biocompatible materials such as ecoflex, polyurethane, hydrogel composites or conductive nanomaterials like graphene and gold nanoparticles (Zhang et al., 2025; Zheng et al., 2023). These platforms detect a wide range of parameters, including heart rate, body temperature, muscle activity, and biochemical markers such as glucose, lactate, and electrolytes in sweat. Epidermal sensors have emerged as powerful tools for personalized health monitoring, clinical diagnostics, sports performance tracking, and continuous physiological assessment in real-world settings due to their non-invasive nature, high sensitivity, and ability to integrate with wireless communication systems (Tong et al., 2025).

The integration of wireless data transmission further enables real-time monitoring, early disease detection, and personalized therapy, positioning epidermal sensors as a foundational technology for next-generation digital healthcare systems (Zheng et al., 2023). Their reliable long-term operation depends on the careful integration of materials and architectures that maintain flexibility, biocompatibility, and adhesion under continuous mechanical and physiological stress. In addition, energy conversion and storage components may be integrated to enhance device autonomy. To enhance autonomy, energy harvesting and storage modules, such as biofuel cells (Di et al., 2025), zinc-ion batteries (Zeng et al., 2024), or nanomaterial-enhanced electrodes (Bae et al., 2022) have been incorporated enabling sustainable power generation alongside biochemical sensing.

Following the selection of materials and substrates, the next generation design lies in constructing efficient electrodes and interconnects

that preserve electrical and mechanical integrity during skin contact. Functional electrodes and interconnects play a central role in determining sensing performance and device durability. For example, Pt nanoparticles (Bae et al., 2022), Ag nanowires (Alathlawi et al., 2025), MXene composites (Enaiet Allah, 2023), and conductive polymers are key materials used to enhance electron transfer kinetics and reduce interfacial resistance. Also, stretchable interconnects maintain electrical conductivity under repeated mechanical deformation, an essential requirement for on-skin application. In addition, integrating architectural components such as porous cellulose channels, serpentine designs, and microneedle arrays (Vulpe et al., 2024) enhances the functional versatility of epidermal sensors, enabling simultaneous fluid handling and signal transduction on the skin (Yang et al., 2021). These architectures establish a robust framework that enables energy autonomy, multiplexed biochemical sensing, and seamless wireless integration, key elements for reliable, continuous, and non-invasive health monitoring (Jeon et al., 2025).

Effective electrochemical transduction is essential to translate biochemical events at the skin interface into accurate electrical signals, i.e., converting molecular interactions on epidermal sensors into reliable electronic readouts. Incorporation of materials such as Prussian blue–nickel hexacyanoferrate composites embedded within crosslinked protein matrices enhances catalytic efficiency and operational stability, while polymer-based ion-selective membranes incorporating specific ionophores minimize drift and enable selective recognition. Localized sweat induction can be achieved via miniaturized iontophoresis electrodes coated with cholinergic agonists (e.g., carbachol hydrogels), enabling sampling without physical exertion.

Physiological conditions (temperature 25–40 °C, pH 6–7.4) are maintained to mimic real-world operation, and the resulting electrochemical signals are captured, amplified, filtered, and wirelessly transmitted via integrated electronics. Calibration protocols accounting for temperature, ionic strength, and sensor drift are critical for accurate real-time quantification, and performance metrics such as sensitivity, selectivity, response time, and long-term stability are validated in both standard solutions and human sweat samples (C. Xu et al., 2024). These transduction strategies underscore the importance of combining biochemical specificity with robust signal processing to deliver clinically meaningful data.

Advanced surface chemistries and microfluidics push epidermal sensors beyond classic enzyme/ion selectivity, widening what they can detect. For example, Wang et al. a laser-engraved graphene (LEG) epidermal biosensor that enables real-time, noninvasive detection of up to 20 amino acids and 4 vitamins in sweat with LOD values of 0.01–0.05 mM. By integrating MIP and redox-active nanoreporters (RARs) functional layers with iontophoresis-based sweat induction and microfluidic sampling, the device achieves stable operation for over 12 h and enables wireless, multiplexed biochemical monitoring for personalized metabolic health assessment. This design demonstrates how epidermal electrochemical biosensors can achieve broad biomarker coverage, including amino acids, vitamins, metabolites, lipids, hormones, and drugs, highlighting their significant potential for at-home monitoring and telemedicine (Wang et al., 2022). To further enhance sensitivity and integration, micro/nano-engineered structures and tailored surface chemistries have been incorporated into epidermal platforms. For instance, thin polyimide substrates (10–20 μm) provide flexibility and skin conformity, while gold or graphene-based electrodes patterned via photolithography or laser processing ensure precise geometries. Functionalization with nanomaterials such as AuNPs or rGO increases electroactive surface area and enhances biomolecular adsorption. PDMS-based microfluidic channels enable continuous sweat delivery and minimize diffusion limitations, whereas selective biorecognition elements enzymes, antibodies, and aptamers, ensure high specificity toward metabolites and electrolytes. The resulting electrochemical signals, generated through amperometry, potentiometry, or impedance spectroscopy, are processed by compact readout circuits and wirelessly

transmitted to external devices (Pérez and Orozco, 2022). By integrating these advanced components, epidermal sensors achieve high-resolution, real-time biochemical monitoring directly on the skin.

Recent advancements extend sensing strategies deep into dermal layer using microneedle-based epidermal sensors enabling minimally invasive access to target. For example, a chemo-responsive microneedle patch for electrochemical detection of the melanoma biomarker tyrosinase directly through human skin tissue was developed. In this system, a polyurethane (PU)/PEDOT: PSS composite substrate provided electrical conductivity, elasticity, and biocompatibility. A 6×6 microneedle array

molded from silicon templates enabled repeated skin insertion without mechanical failure. The electrode surfaces were functionalized via silanization and glutaraldehyde coupling allowing selective enzymatic oxidation of tyrosinase. The platform showed a linear range of 0.3–0.7 mg/mL, an LOD of 0.06 mg/mL, high sensitivity, and good reproducibility (Poursharifi et al., 2024).

In another study, microneedle-based systems have been designed for gas and ion sensing. The system incorporated three stainless-steel microneedles embedded in silicone, with two serving as pH- and carbonate-selective working electrodes and the third as a solid-state Ag/

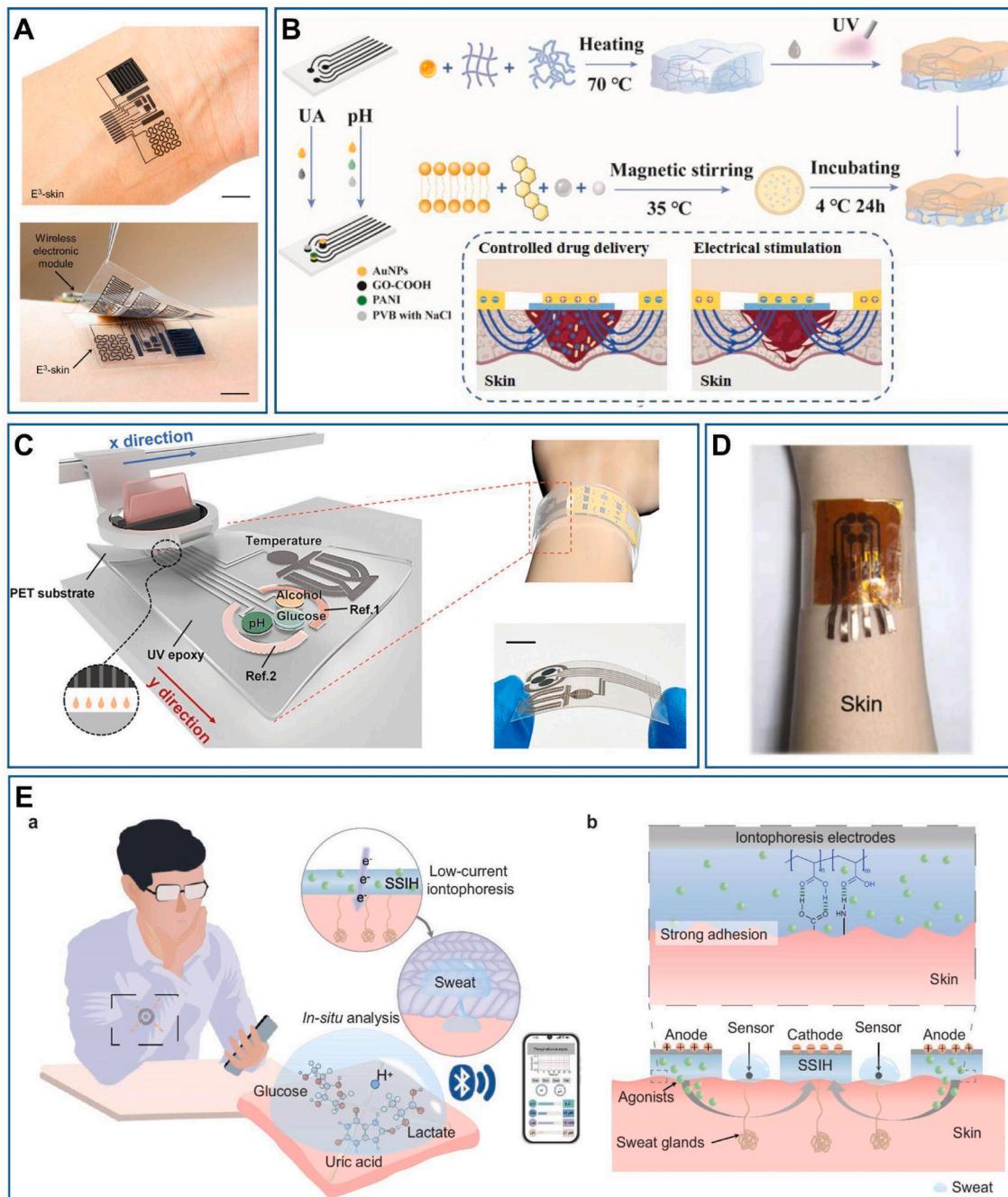


Fig. 5. Representative next-generation epidermal biosensing platforms. A) 3D-printed epifluidic electronic skin with a wireless module, enabling simultaneous biochemical and mechanical sensing on the skin (Song et al., 2023). B) Closed-loop wound-care patch that monitors infection-related biomarkers (pH, uric acid, temperature) and controls local antibiotic release (Wang et al., 2025). C) Fully inkjet-printed multiplexed epidermal platform for simultaneous monitoring of glucose, alcohol, pH, temperature, and reference signals (Ma et al., 2024). D) Laser-induced graphene-based ion-selective sensor for real-time Na^+ , K^+ , and pH monitoring during exercise (Liao et al., 2022). E) Textile-based epidermal system combining iontophoresis-induced sweat stimulation with fiber-integrated electrochemical sensors for long-term on-body measurements (Zhou et al., 2025). All images adapted with permission from the respective publishers.

AgCl reference electrode. Wireless data transmission via Bluetooth-enabled potentiometers supported real-time on-body measurements, and both *ex-vivo* and *in-vivo* evaluations showed strong correlation between ISF and blood CO₂ levels, validating its use as a noninvasive alternative to blood gas analysis (Molinero-Fernandez et al., 2024). Microneedle-based epidermal biosensors mark a shift from passive surface monitoring to minimally invasive, physiologically relevant diagnostics. By accessing dermal biofluids while preserving comfort and mobility and integrating micro/nano-engineered electrodes, biocompatible polymer substrates, and wireless readouts, they extend epidermal sensing beyond superficial sweat to deeper-layer analysis. This evolution improves analytical accuracy and enables continuous subdermal biochemical mapping with greater clinical relevance.

Next-generation epidermal systems integrate biochemical, biophysical, and therapeutic functions as illustrated in Fig. 5. For example, multimodal e-skin platforms (Fig. 5A) integrate biochemical and mechanical sensing with iontophoresis-driven sweat induction and soft microfluidics, enabling high-resolution physiological mapping during natural activities (Song et al., 2023). When coupled with machine learning algorithms, these platforms move beyond raw data acquisition toward predictive and adaptive analytics, a major step toward personalized health management. Despite these advances, challenges remain in power consumption, standardized data processing, and algorithm generalizability across users.

Expanding from passive monitoring to active intervention, theranostic epidermal systems have developed to detect and treat health conditions. In wound management, epidermal theranostic systems (Fig. 5B) combine electrochemical detection of infection biomarkers (pH, uric acid, temperature) with smart hydrogels capable of controlled antibiotic release (Wang et al., 2025). This closed-loop strategy enables autonomous therapy while reducing overtreatment and antimicrobial resistance. However, achieving precise drug dosing, ensuring long-term biocompatibility, and meeting regulatory standards remain key challenges limiting clinical translation. In parallel, scalable and multiplexed sensing platforms have been emerged for metabolic and lifestyle monitoring in real-world settings. For instance, fully inkjet-printed multiplexed platform (Fig. 5C) was developed to enable scable fabrication, precise material deposition, drift suppression, and wireless integration for the simultaneous detection of glucose, alcohol, pH, and temperature (Ma et al., 2024). Although promising for personalized health monitoring, these systems face limitations due to enzyme degradation, inter-user variability in sweat composition, and the need for frequent calibration. To overcome these limitations, low-cost laser-induced graphene (LIG)-based ion-selective sensors (Fig. 5D) have been introduced, offering excellent flexibility and rapid ion detection of Na⁺, K⁺, and pH for real-time electrolyte balance monitoring during exercise (Liao et al., 2022). However, ion-selective membranes are prone to biofouling, drift, and cross-sensitivity, necessitating self-calibration or protective strategies to maintain long-term accuracy. To overcome the limited sweat availability in sedentary or clinical populations, textile-based epidermal biosensing systems with active sweat induction have been developed (Zhou et al., 2025). In these systems, low-current iontophoresis through skin-compatible hydrogel electrodes stimulates sweat secretion, while fiber-based sensors continuously monitor multiple biomarkers over extended periods (Fig. 5E). These platforms provide enhanced comfort, long-term wearability, and improved biomarker accessibility, representing a significant step toward real-world applicability. Nonetheless, challenges related to washability, mechanical durability, and stable skin contact must be addressed to ensure reliable performance and successful commercialization.

These advances highlight the evolution of epidermal biosensors from simple single-analyte devices to intelligent, multifunctional systems capable of real-time, multimodal data acquisition with high sensitivity and seamless skin integration. Their main strengths lie in analytical precision, wireless connectivity, and the potential for closed-loop and AI-assisted health monitoring. However, challenges such as long-term

stability, biofouling, calibration drift, and variability in biofluid composition still hinder clinical translation. Maintaining reliable skin adhesion, ensuring biocompatibility during prolonged use, and integrating durable power and data modules into flexible designs also remain difficult. Continued progress in materials science and bio-interface engineering will be crucial to achieving reliable long-term operation and large-scale deployment. Textile-integrated platforms, offering improved comfort and wearability, mark an important step toward real-world applications, although issues like washability and mechanical durability must still be addressed for successful commercialization. Representative examples of wearable biosensors categorized by biofluid, detection method, analyte, application, and detection range are summarized in Table 1.

In summary, Epidermal and ISF-focused wearables mainly rely on electrochemical redox reactions, impedance measurements, or affinity-based recognition (enzymes, antibodies, aptamers, MIPs) to quantify target analytes. Microneedle-based and ultrathin “electronic skin” platforms access interstitial fluid or on-skin biofluids with stretchable conductive networks (e.g., gold, graphene, MXenes), while integrated microfluidic structures help control fluid transport and reduce motion-induced signal artefacts. Epidermal and ISF-focused wearables include microneedle patches, ultrathin electronic skins, and stretchable electrochemical or impedance-based devices. Their strengths lie in continuous access to interstitial fluid and improved correlation with blood biomarkers compared to surface sweat. Microneedles provide minimally invasive sampling and enhanced signal fidelity, while ultrathin skins conform well to mechanical deformation. Key limitations include mechanical strain, adhesion instability, long-term biocompatibility, and regulatory considerations for minimally invasive technologies. These devices show strong translational promise but require robust packaging and durable interfaces.

2.5. Non-biological physical sensors

Wearable sensors are regarded as a major class of noninvasive diagnostic tools that bridge the gap between traditional clinical measurements and continuous personal health monitoring. While biological biosensors rely on biorecognition elements such as enzymes or antibodies to detect specific biomarkers (Xue et al., 2024), non-biological wearable sensors focus on the measurement of physical signals, including heart rate, electrocardiogram (EKG), blood pressure, pulse, respiration, and posture in real time (Vo and Trinh, 2024). These sensors are manufactured from innovative materials such as flexible polymers, conductive inks, and nanomaterials, and are designed as smartwatches, skin-adhesive patches, or smart clothing. The greatest promise of this technology is to transform healthcare from a reactive model to a proactive and personalized one. In this way, instantaneous measurements that were once limited to hospitals can now be conveniently performed by people in their homes, enabling early diagnosis. Based on their sensing mechanism, non-biological wearable sensors can be broadly categorized into four main groups, including mechanical signal sensors, electrical signal sensors, optical signal sensors, and thermal signal sensors.

Mechanical signal sensors operate by directly measuring physical forces such as pressure, tension, acceleration or vibration generated by the human body. Among the various physiological signals in the human body, mechanical signals are the most prominent for monitoring vital parameters, including blood pressure, pulse, and plantar pressure. Typical mechanical sensors include accelerometers, gyroscopes, and pressure sensors. Accelerometers measure the linear acceleration and orientation of the body or specific body parts relative to gravity (Gibbs and Asada, n.d.), whereas a gyroscope is an active sensor that measures its own angular velocity (gyration) and can detect very small angular displacements caused by cardiac activity (Sieciński et al., 2020). Fig. 6 shows the mechanism, fabrication, and application for non-biological physical wearable sensors.

Table 1

Representative examples of wearable biosensors categorized by biofluid, detection method, analyte, application, and detection range.

Biofluid	Measuring method	Analyte	Application	Linear Range (LR) or Limit of Detection (LOD)	Reference
Tear	Colorimetric detection with smartphone-integrated eye-patch biosensor	H ⁺ ion Ascorbic Acid Glucose Albumin	Non-invasive simultaneous monitoring of multiple tear biomarkers	LR for ascorbic acid: 0.01–12 mM LR for glucose: 0.15–2.5 mM LR for albumin: 0–10 g/L	Xu et al. (2022)
Tear	Optical fiber-ball-resonator biosensor (Wearable eye-goggle device)	Lipocalin-1 protein	Non-invasive detection of diabetic retinopathy biomarker in tears	LOD ≈ 0.00024 ng mL ⁻¹	Gomez et al. (2024)
Tear	Fluorometric detection with a sodium-sensitive silicone-hydrogel contact lens	Na ⁺ ion	Non-invasive monitoring of tear electrolyte levels for dry-eye diagnostics	LR: 0–150 mM Na ⁺	Badugu et al. (2021)
Tear	Fluorometric detection using a contact lens integrated with a lysozyme-sensitive fluorescent dye	Lysozyme	Non-invasive analysis of lysozyme concentration in tear fluid for dry-eye disease diagnosis	LR: 2.4–10.7 µg/mL	Ballard et al. (2020)
Tear	Electrochemical detection with a soft wireless smart contact lens integrated with a wireless interface and a low-potential redox mediator	Cholesterol	Non-invasive real-time monitoring of tear cholesterol for hyperlipidemia diagnosis	LOD: 9.91 µM	Song et al. (2022)
Tear	Optical dual-functional contact lens combining structural colorimetry for IOP and SERS	IOP matrix MMP-9	Non-invasive simultaneous monitoring of IOP and biomarker in tears	LOD ≈ 0.9 ng mL ⁻¹	Ye et al. (2022)
Sweat	Non-enzymatic electrochemical sensing with CuO-nanocomposite modified glassy carbon electrode	Lactic acid	Non-invasive monitoring of Lactic acid in sweat for health/performance diagnostics	LOD ≈ 0.027 mM	Sajna et al. (2023)
Sweat	Disposable electrochemical device using conductive ink modified with Prussian Blue; DPV for uric acid & non-enzymatic Amperometry for H ₂ O ₂ and enzyme-based glucose detection	Uric acid H ₂ O ₂ Glucose	Low-cost wearable-type sweat sensor for point-of-care monitoring of uric acid, H ₂ O ₂ (as mediator), and Glucose	LOD for H ₂ O ₂ : 31.6 µM LOD for glucose: 9.20 µM	Blasques et al. (2022)
Sweat	Microfluidic electrochemical integrated device, amperometric detection	Glucose	Non-invasive real-time monitoring of sweat glucose for diabetes management	LR: 0–2.0 mM (sensitivity ≈ 16.8 µA/mM/cm ²) LR: 1 mM–1000 mM	Noura et al. (2022)
Sweat	Potentiometric detection using a butterfly-like paper-based microfluidic device with screen-printed electrodes	Na ⁺	Non-invasive real-time sweat monitoring for dehydration and exercise-effort analysis	LR: 1 mM–1000 mM	Fiore et al. (2024)
Sweat	Multiplexed electrochemical sensing with LIG electrodes using amperometric and potentiometric readouts integrated with Bluetooth	Glucose, Lactic acid Na ⁺ K ⁺	Non-invasive real-time multiplexed monitoring of metabolites and electrolytes in sweat	LOD for glucose: 0.191 µM LOD for lactic acid: 0.167 µM	Park and Pak (2024)
Saliva	Potentiometric detection using wire-type solid-state ion-selective electrodes embedded in PDMS-PEG microfluidic channel	Na ⁺ , K ⁺	Non-invasive real-time continuous monitoring of salivary electrolytes in neonates via smart pacifier	LR for Na ⁺ : ~5.7–9.1 mM; (Sensitivity ≈ 52 mV/dec) LR for K ⁺ : ~4.2–5.2 mM (Sensitivity ≈ 57 mV/dec)	Lim et al. (2022)
Saliva	Electrochemical pH sensing and electrically controlled release	H ⁺ (pH) and Fluoride (F ⁻)	In situ oral microenvironment monitoring and on-demand fluoride therapy for caries	LR for pH: 3–8 (Sensitivity: 62.97 mV/decade) LR for Fluoride: 5–100 µM (LOD: ≈5 µM)	Shi et al. (2022)
Saliva	Wearable hydrogel-based radio frequency (RF) sensor	Hydrogen sulfide (H ₂ S)	Real-time periodontitis monitoring and simultaneous antibacterial chlorhexidine release	LR: 2–30 µM LOD: 1.2 µM	Pan et al. (2024)
Saliva	Ring-based sensor platform	THC and alcohol	Rapid roadside screening for cannabis and alcohol use	LOD for THC: 0.5 µM LOD for alcohol: 0.2 mM	Mishra et al. (2020)

Abbreviations: IOP: Intraocular pressure; NFC: Near Field Communication; SERS: Surface Enhanced Raman Spectroscopy; MMP-9: matrix metalloproteinase-9; H₂O₂: hydrogen peroxide; LIG: Laser-induced graphene; THC: Δ9-tetrahydrocannabinol.

The increasing prevalence of cardiovascular and respiratory diseases has driven demand for wearable systems capable of simultaneously monitoring heart rate (HR) and respiratory rate (RR) using inertial measurement units (IMUs) that integrate both accelerometers and gyroscopes (Romano et al., 2022). Early studies explored the feasibility of cardiac monitoring through accelerometer- and gyroscope-based sensors integrated into smart devices such as Google Glass, smartwatches, smartphones, and chest patches (Migeotte et al., 2016). Advances in microelectronics and signal processing have since enabled the conversion of cardiac vibration recordings into reliable diagnostic tools for cardiovascular assessment (Casanella et al., 2019). For instance, a signal processing algorithm using smartphone accelerometers to measure ultra-short-term heart rate variability for stress detection was developed. The technique involved placing a smartphone on the abdomen and analyzing ballistocardiographic (BCG) signals through cross-correlation with heartbeat templates (Landreani et al., 2019).

Beyond cardiovascular applications, mechanical sensors have also

been applied in orthopedic diagnostics. Conventional methods for acute joint injuries and chronic conditions such as osteoarthritis involve a combination of medical imaging, which can be costly and time-consuming, and physical examination, which often relies on subjective assessments by the clinician or patient. To address these limitations, a novel system was proposed that embeds accelerometer-based sensors into the fingertip of a glove to noninvasively detect vibrational signals from the knee joint, demonstrating potential for diagnosing conditions such as osteoarthritis (Bolus et al., 2019) as shown in Fig. 6A. This work is considered an important step for future wearable sensor systems for the diagnosis and monitoring of joint disorders such as knee osteoarthritis.

However, traditional accelerometers are typically rigid and uncomfortable for long-term use. Recent research has introduced piezoelectric, piezoresistive, and capacitive sensors that offer high flexibility and sensitivity (Ji and Zhang, 2022). Piezoelectric sensors convert mechanical deformation into electrical charge without an external power

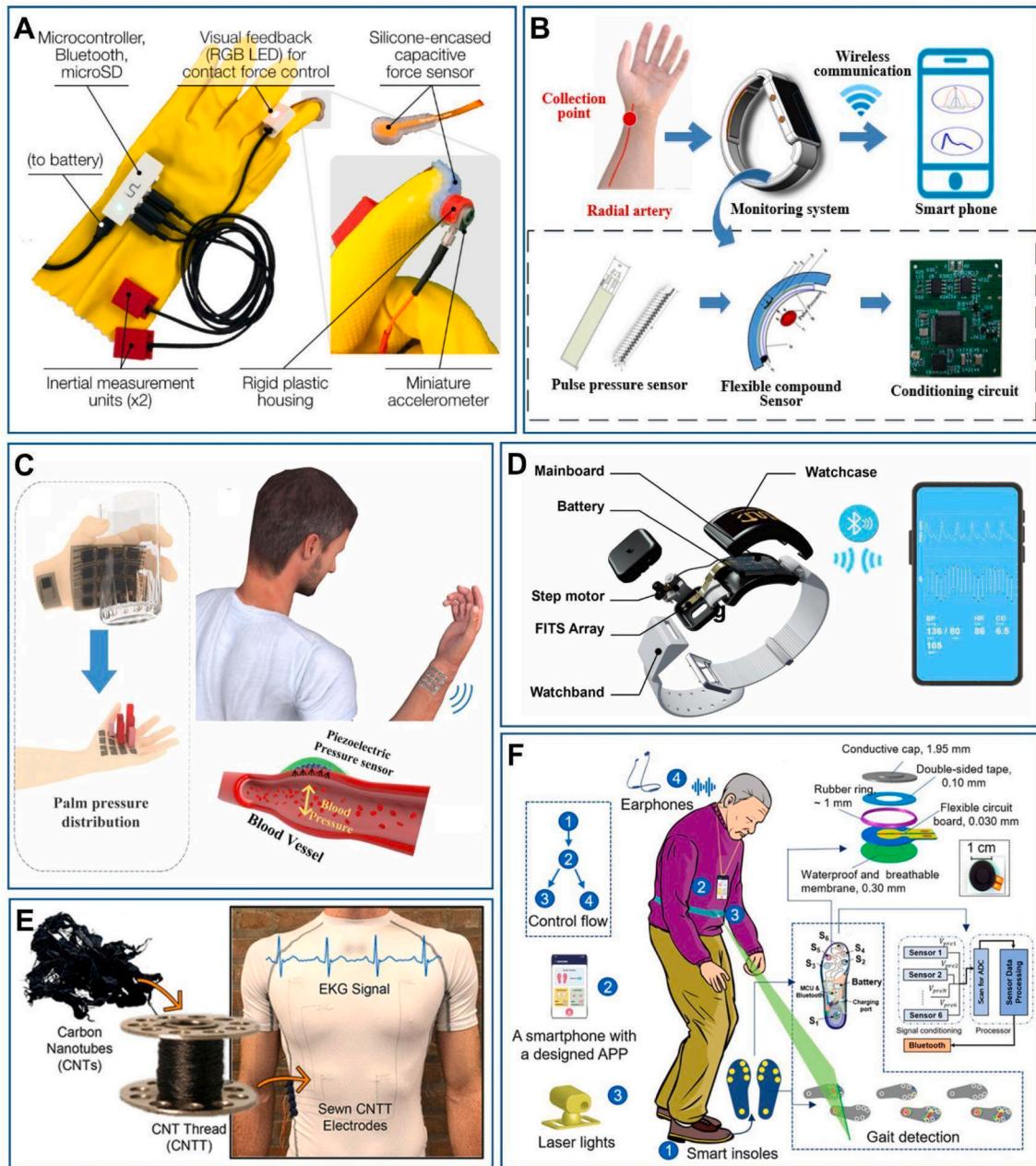


Fig. 6. Representative non-biological physical wearable sensors. **A)** Glove with embedded accelerometers for capturing joint sounds (Bolus et al., 2019). **B)** The pulse wave monitoring system (Kang et al., 2022). **C)** The schematic of the preparation and various applications of MXene fabric-based sensors (Chen et al., 2025). **D)** Schematic illustration of the FAST device (Deng et al., 2024). **E)** The schematic illustration of ECGs obtained by carbon nanotubes (Taylor et al., 2021). **F)** Illustration of the IWS structure and function worn by a person with Parkinson's disease (Yang et al., 2022). All images adapted with permission from the respective publishers.

source, providing compactness, low power consumption, and a high signal-to-noise ratio ideal for wearable and the Internet of Things (IoT) applications. Due to their scalability and sensitivity, they are widely used in industries ranging from healthcare to consumer electronics. In a recent study, a high-sensitivity piezoelectric sensor containing polyvinylidene fluoride (PVDF) was developed, as shown in Fig. 6B. This sensor detects even the slightest pressure changes created by the pulse wave, considering the problem of the pressure between the sensor and the skin changing during the user's arm movements, which degrades the signal quality and leads to erroneous measurements (Kang et al., 2022). Similarly, a serpentine-structured PVDF strain sensor was designed for simultaneous respiration and heart rate monitoring, demonstrating excellent flexibility and skin conformity (Ji and Zhang, 2022).

Following these, capacitive-flexible pressure sensors are another

widely researched type of pressure sensor and share many similarities with piezoresistive sensors. Compared to pressure sensors with different operating principles, capacitive-flexible pressure sensors offer advantages such as faster response times and lower power consumption (Chen and Yan, 2020). In one study, PDMS polymer containing barium titanate (BaTiO_3) nanoparticles was used as the dielectric layer and PDMS containing multi-walled carbon nanotubes (MWCNTs) served as the electrode, resulting in a highly sensitive sensor. This developed sensor was placed on the sole of a shoe and successfully detected pressure changes that occurred under different motion conditions, and using these data, the type of motion was classified with 94 % accuracy. The basic operating principle of the sensor is that the flexible dielectric layer becomes thinner when pressure is applied, and the capacitance changes accordingly (Yu et al., 2021). This proves the feasibility of the human action

recognition system based on a flexible wearable sensor. Furthermore, the system has high application potential in the field of wearable action sensing.

Piezoresistive pressure sensors have been widely studied and applied due to their simple structure and operating mechanism, relatively simple manufacturing process, and excellent performance. A recent microfluidic pressure sensor developed using conductive MXene nanosheets and an electrospun thermoplastic polyurethane (TPU) nanofiber membrane exhibited remarkable flexibility, air permeability, and user comfort, making it well-suited for long-term skin contact (Chen et al., 2025).

Fig. 6C shows a flexible, breathable pressure sensor that detects wrist pulses for ML-based blood-pressure estimation, with 652.1 kPa^{-1} sensitivity, 0–60 kPa range, and 1 Pa resolution. In another study, Deng et al. developed a fully wearable tonometry system called flexible adaptive sensing tonometry (FAST) that provided continuous monitoring of hemodynamic parameters with medical-grade precision (**Fig. 6D**). This system integrates a 1×8 flexible ionotronic sensing array with a closed-loop motorized motion mechanism. The sensor array can precisely locate the radial artery and simplifies the traditional dual-axis application process into a single-axis approach. During the measurement process, a self-calibration algorithm enables continuous prediction of the intra-arterial pressure waveform. In tests with healthy volunteers, the FAST system achieved pulse wave, blood pressure, and other hemodynamic measurements that were comparable in accuracy to clinical reference instruments (Deng et al., 2024).

Comparative studies have evaluated the relative performance of piezoresistive and piezoelectric sensors in detecting different gait phases (Zhang et al., 2022). These approaches aim to determine which of these two sensor types is more reliable and useful in detecting different phases of walking. They have developed a smart shoe insole system that includes both sensor types. Both piezoelectric and piezoresistive sensors are placed at strategic points on the insole, such as the heel and toe. This allows for simultaneous data collection from both sensors during the same walking motion.

Electrical wearable sensors are compact, typically non-invasive devices that can be worn on the body or integrated into clothing, continuously monitoring physiological and biochemical data in real time. These sensors are designed as single-use patches that are integrated to the body to provide long-term monitoring, and chest straps are used by athletes (Pereira et al., 2020), smart clothing such as shirts, vests, or bras with EKG electrodes directly integrated into the fabric and wrist-worn devices, smartwatches and wristbands (Bumgarner et al., 2018). The most common use of these sensors is for arrhythmia detection and monitoring, particularly for identifying potentially serious atrial fibrillation (AF). Beyond clinical diagnostics, these sensors are also used for remote patient monitoring, post-operative follow-up, general cardiovascular assessment, and athletic performance tracking.

Recent research has focused on improving signal stability and comfort by replacing traditional wet electrodes with dry alternatives. A new PDMS dry electrode overcomes Ag/AgCl gel electrodes' tendency to dry out, reducing skin irritation and performance loss (Fayyaz Shahandashti et al., 2019). The resulting dry electrode system offers high conductivity, comfort, and durability, enabling long-term and high-quality signal acquisition in wearable biosensors. Further advancements have expanded electrical biosensing beyond cardiac activity to include simultaneous brain and heart monitoring. Since stress manifests through both mental (EEG) and physical (ECG) responses (Pan and Li, 2007), researchers proposed a dual-signal system capable of detecting both types of activity (Ahn et al., 2019). The resulting lightweight and user-friendly device, designed to be worn behind the ears, simultaneously records electroencephalogram (EEG) and heart rate variability (ECG-HRV) using a small number of electrodes positioned behind the ears and on the forehead. This innovative dual-mode biosensor can accurately evaluate stress levels by synchronously capturing neural and cardiac activity.

Significant progress has been made in electronic textiles (e-textiles),

which aim to integrate electrical biosensing components into flexible fabrics. Despite the widespread adoption of rigid smartwatches, advancements in e-textiles have been slower due to challenges in combining conductive electronics with soft, deformable fibers (Taylor et al., 2021). To address this, researchers developed washable, sewable all-CNT threads to serve as electrodes and signal wires suitable for integration into wearable textiles (**Fig. 6E**). By stitching conductive CNT threads directly into fabric, they achieved soft, flexible, skin-compatible conductive pathways with metal-like conductivity and low interface impedance. ECG recorded through these carbon threads matched those obtained using conventional electrodes, showing no statistically significant difference. Moreover, the textile-integrated threads withstood repeated mechanical stress and machine washing without signal degradation. The results demonstrate that CNT thread-based conductive elements can seamlessly blend with standard clothing manufacturing techniques, offering a promising platform for smart clothing and e-textiles.

Optical sensors are clearly different from the sensors mentioned above, which do not undergo direct changes in their electrical properties due to external forces. The performance of optical sensors, consisting of a light source, optical fiber, and detector, is primarily dependent on the optical fiber. When exposed to external forces, deformation of the optical fiber causes changes in the optical path within the fiber, leading to spectral shifts in the reflected light wavelength (Hari M and Rajan, 2021). These sensors have emerged as a promising alternative for smart health monitoring because traditional electronic sensors are sensitive to electromagnetic interference. Applications span chronic disease management, athlete performance tracking, fall detection in older adults, and everyday health/fitness monitoring. By enabling continuous, non-invasive measurements, these sensors advance personalized, preventive medicine (Jha et al., 2024).

For example, optical fiber sensors have gained significant attention in hand and finger rehabilitation, a field of growing importance with the aging global population (Leal-Junior et al., 2020). These sensors demonstrated high sensitivity, immunity to electromagnetic interference, and multi-parameter sensing capabilities, making them suitable for tracking fine motor activity, touch, and temperature through integration into gloves or textile platforms. However, challenges such as high production costs, integration complexity, motion-induced errors, and limited long-term stability remain. Future developments aim to create flexible, low-cost, and wireless optical sensors enhanced with machine learning-based signal processing to enable real-time rehabilitation and health monitoring (Li et al., 2024).

Beyond rehabilitation, optical sensing technologies have also been applied in neurological disorder management. For instance, in the case of Parkinson's disease, which impairs motor control and causes tremors and freezing of gait (FoG), an intelligent wearable system (IWS) was developed to detect FoG episodes in real time and assist patients in restoring movement as shown in **Fig. 6F**. This system integrates pressure-sensing insoles, a fast gait-recognition algorithm, and wireless visual-auditory cueing devices to prompt users during freezing episodes. In trials with 29 participants, offline FoG detection reached 97 % accuracy, while live tests with 16 patients achieved 94 % accuracy with an average response latency of 0.37 s. User feedback indicated high satisfaction; most participants found the system comfortable and effective in improving gait continuity. Overall, this intelligent wearable system offers a promising assistive technology for reducing gait disturbances and enhancing mobility in individuals with Parkinson's disease (Yang et al., 2022).

Body temperature is a vital health parameter that often requires accurate, continuous tracking. Conventional thermometers and infrared devices are suitable for spot checks but inadequate for real-time monitoring during movement or at localized sites (e.g., wounds, tumors). To overcome these limitations, flexible, wearable temperature sensors have been developed that are thin, portable, and capable of high sensitivity and precision (Su et al., 2020). These sensors exploit

temperature-induced changes in heat-sensitive materials to generate electrical signals, enabling continuous, noninvasive body temperature monitoring.

Flexible thermal sensors are also being integrated into smart environments to improve comfort and energy efficiency via personalized temperature control. To address the limitations of conventional thermal comfort models (e.g., PMV), which neglect individual variability, researchers are developing wearable sensor-based personal comfort models that infer each person's thermal preferences from wearable temperature and physiological data, rather than predicting average human responses (Liu et al., 2019).

Wearable physical sensors such as strain/pressure sensors, ECG/EEG electrodes, PPG modules, inertial units, and temperature sensors typically adopt textile-integrated, patch-based, or smartwatch-like architectures. Their main advantages are high robustness, user acceptance, and reliable long-term operation. Electrochemical or optical biosensing can be synergistically combined with these platforms for multimodal monitoring. Limitations arise from mechanical noise, motion artefacts, environmental variability, and limited biochemical specificity. These sensors form the backbone of current commercial wearables and provide a stable platform for future integration with biochemical sensing.

3. Trends and future perspectives

Several commercially available wearable sensors have emerged in recent years, reflecting the rapid translation of laboratory research into practical health monitoring solutions (Table 2). These devices are designed to track a wide range of physiological and biochemical parameters, including heart rate, body temperature, glucose levels, oxygen saturation, and physical activity, through non-invasive or minimally invasive approaches. Combining advanced materials, microelectronics, and wireless connectivity, they enable real-time data acquisition and integration with mobile health platforms. Such products not only enhance personalized healthcare and fitness tracking but also pave the way for continuous, remote, and preventive health management.

The wearable-sensing market is converging across medical devices, consumer electronics, sports, and occupational safety, moving from single-analyte gadgets toward multimodal, skin-conformal platforms that combine biochemical and physical signals on the same device. Technical progress is driven by flexible materials, printed electrodes, breathable textiles, and microfluidics that deliver fresh biofluid with low reagent use. The future of wearable biochemical and physical sensing technologies will depend on progress across four interconnected areas. First, clinical translation and standardized on-body validation remain essential. Regulatory pathways are also maturing for software-as-a-medical-device and adaptive algorithms, yet consistent clinical

Table 2
Examples of commercially available wearable sensors.

Product	Biomarkers/Parameters	Wearable System	Measurement Method	Typical User	Regulatory Status	Website
Epicore Biosystems' Gx Sweat Patch	Sweat rate, sodium loss, electrolyte concentration, fluid loss	Skin-interfaced microfluidic patch	Colorimetric assays integrated with microfluidic channels; data analyzed via smartphone image processing	Athletes, fitness enthusiasts	Consumer wellness device	https://www.epicorebiosystems.com/
Nix Hydration Biosensor	Electrolyte concentration, fluid loss, sodium levels	Skin-mounted microfluidic patch	Electrochemical impedance spectroscopy with algorithm-based hydration estimation	Endurance athletes, runners and cyclists	Consumer wellness device	https://nixbiosensors.com/
Dexcom G7	Glucose (interstitial fluid)	Skin-worn sensor with wireless transmitter	Subcutaneous electrochemical sensing with real-time data transmission to a smartphone	Individuals with Type 1 and Type 2 diabetes	FDA-cleared medical device	https://dexcomtr.com/
Abbott FreeStyle Libre 3	Glucose (interstitial fluid)	Skin-mounted sensor (Upper arm)	Continuous subcutaneous electrochemical glucose monitoring	Individuals with Type 1 and Type 2 diabetes	FDA-cleared medical device	https://www.freestyleabbott-tr/tr/home.html
Eversense E3	Glucose (interstitial fluid)	Implantable sensor with removable transmitter	Fluorescence-based glucose detection with continuous wireless data transfer	Long-term continuous glucose monitoring (CGM) users	FDA-approved implantable CGM system	https://global.eversensedabetes.com/
BSX Insight	Lactate threshold, local metabolic activity	Wearable optical band	Near-infrared optical spectroscopy for metabolic monitoring	Endurance athletes, cyclists and triathletes	Consumer sports device	https://wearables.com/
Apple Watch Series	Heart rate, SpO ₂ , ECG, arrhythmia detection, sleep quality, activity metrics	Smartwatch	Optical Photoplethysmography and Electrocardiogram sensors with red/infrared pulse oximetry; motion analysis via accelerometer and gyroscope	General consumers, fitness users, and individuals tracking cardiac health	FDA-cleared ECG feature and SpO ₂ as wellness features	https://www.apple.com/
FluidLogic GPR50 Hydration System	Estimated sweat loss, fluid balance	Smart wearable hydration pack	Micro-pump control with haptic feedback and app-based algorithmic hydration tracking	Motorsports athletes, cyclists and tactical users	Consumer performance device	https://fluidlogic.com/
StretchSense Motion Capture Glove	Hand gestures, finger joint motion, and grip dynamics	Smart glove with textile-integrated stretch sensors	Capacitive/stretch sensing integrated in fabric; wireless real-time motion data transmission	VR/AR users, animators, robotics and motion-capture professionals	Commercial device, non-medical	https:////stretchsense.com/
SENSIMED Triggerfish®	Intraocular pressure fluctuations	Contact-lens-based sensor	Strain gauge embedded in lens detects corneal shape changes; wireless data transmission to recorder	Glaucoma patients and ophthalmology clinics	FDA-cleared medical device	https://www.sensimed.ch/
Hexoskin Smart Shirt	Heart rate, heart rate variability, respiration rate, ventilation, activity, sleep metrics	Smart textile shirt with embedded sensors	Textile Electrocardiogram electrodes and inductive plethysmography bands; 3-axis accelerometer; Bluetooth data transfer	Athletes, health-tracking consumers and sleep researchers	Consumer wellness/fitness device	https://hexoskin.com/
Sensoria Smart Socks	Step cadence, gait pattern, ground contact time, impact forces	Smart textile socks with detachable Bluetooth anklet	Textile pressure sensors with integrated inertial sensing (accelerometer/gyroscope); wireless data transmission	Runners, gait analysis users and rehabilitation patients	Consumer wellness/sports device	https://www.sensoriafitness.com/smartsocks/

validation remains a bottleneck. Although numerous proof-of-concept devices have demonstrated promising performance in sweat, tear, saliva, and epidermal sensing, large variations in sampling conditions and limited clinical datasets continue to hinder medical adoption. Future studies must employ harmonized on-body testing protocols, multi-center comparisons, and reference-grade clinical benchmarks to ensure reproducibility and regulatory compatibility. Second, the integration of data analytics, artificial intelligence, and privacy-preserving frameworks is becoming increasingly important. Many of the devices discussed in this review generate high-frequency, multimodal data streams that require robust preprocessing, drift compensation, and context-aware machine learning. Future systems should balance on-device processing with cloud-based analytics, while addressing privacy, data ownership, interoperability, and long-term calibration. Establishing standardized data formats will be critical for cross-platform comparison and clinical validation. Third, the issues of power management, energy harvesting, and form factor will strongly influence real-world usability. Although several recent devices incorporate flexible batteries or rely on low-power electrochemical sensing, continuous operation in real-world settings demands more efficient energy architectures. Emerging approaches including triboelectric, piezoelectric, and RF energy harvesting should be further integrated with compact electronics to enable battery-free or long-lived wearable systems. Manufacturing, reliability, and cost considerations will also determine the scalability of these technologies. Future progress must focus on scalable roll-to-roll fabrication, robust encapsulation strategies, long-term stability under mechanical strain, and realistic cost models aligned with consumer or clinical markets. Clearer regulatory pathways, including ISO-compliant testing and early engagement with regulatory agencies, will facilitate smoother translation from lab prototypes to commercial products. The sector is transitioning from proofs-of-concept to clinically meaningful, cost-effective, and interoperable platforms that support preventive and personalized care at scale.

CRediT authorship contribution statement

Fatma Kurul: Writing – original draft, Visualization, Methodology, Investigation, Data curation, Conceptualization. **Damla Aydogan:** Writing – original draft, Visualization, Methodology, Investigation, Conceptualization. **Sevval Janat:** Writing – original draft, Visualization, Methodology, Investigation, Conceptualization. **Irem Aydin Kurlangic:** Writing – original draft, Visualization, Investigation, Conceptualization. **Hüseyin Oğuzhan Kaya:** Writing – original draft, Visualization, Supervision, Investigation, Conceptualization. **Seda Nur Topkaya:** Writing – original draft, Visualization, Supervision, Resources, Investigation, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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