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Epidermal wearable optical sensors for sweat monitoring

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Wearable optical sensors have emerged as a promising technology, opening up a new way to monitor human sweat. With the advancement of integrated optical devices, optical materials, and structure design, the current optical skin interfaces primarily employ four analytical methods to transmit sweat chemical information into optical signals: colorimetry, surface-enhanced Raman spectroscopy, fluorescence, and electrochemiluminescence. To improve portability, many external laser source devices and imaging modules are upgraded based on different optical methods. Here, we summarize recent progress in optical sweat sensors, focusing on their principles, development, advantages, and limitations. Finally, current challenges and future prospects of wearable optical sensors in materials, sweat collection, data analysis, and external integrated electronics are discussed.

Wearable sensors gradually expand monitoring functions like heart rate, sleep, and sports with the advancement of materials, integrated circuits, and flexible electronics^{1–8}. Physical sensor play a major role in current wearable devices. Such as: the phototransistor measures blood flow and heart rate, and the accelerometer tracks user activity. While human's comprehensive physiological status needs to be captured collaboratively by chemical sensors and physical sensors^{9–11}. Sweat, as a biofluid, encapsulates a wealth of physiological insights, containing electrolytes, metabolites, nutrients, hormones^{9,12–17}. It exhibits a certain correlation with blood and has revealed significant value in personalized healthcare, sports, disease diagnosis^{18,19}. For example, sweat chloride level can screen cystic fibrosis, sweat glucose level as a potential indicator of diabetes, and sweat ethanol analysis can be used to verify the intake of alcohol^{20–22}. Furthermore, sweat can be acquired non-invasively and continuously on the skin, avoiding the discomfort and intermittency caused by the collection of blood, interstitial fluid (ISF), and urine. Therefore, sweat serves as an appealing biofluid and has been widely used in wearable chemical sensors.

Recent advancements in integrated circuits and wireless communication technology support electrochemical epidermal sensors that convert chemical signals into electrical ones^{23–27}. These platforms mainly employ amperometric, potential, and voltametric analytical methods^{28,29}. Different with electrochemical sensors, which rely on complex, precise circuits and batteries, optical devices represent a new strategy in the evolution of sweat analysis technology due to their uncomplicated structure, compact size^{15,30}. Colorimetry, surface-enhanced Raman scattering (SERS), fluorescence, and electrochemiluminescence (ECL) are applied in wearable optical skin-interfaced for sweat analysis^{31–35}. Chemical signals in sweat are converted

into optical signals through chromophore or fluorophore molecules and more. Subsequently, this physiological information can be interpreted directly or read through external devices such as smartphone and portable Raman spectrometers. The integration of optical sensing with recent advanced flexible devices and microfluidic techniques has gradually accelerated the development of integrated and flexible optical platforms for the collection and analysis of sweat^{14,30,36}.

This review provides the development of wearable optical sweat sensors (Fig. 1). First, we summarize recent advancements in wearable optical sweat sensors based on colorimetric, SERS, fluorescence, and ECL mechanisms, from principle, materials, structures, applications, and limitations. Then, we discuss the current challenges encountered by wearable optical sweat sensors and outline potential directions for their prospects.

Wearable optical sweat sensor

Sweat is secreted from eccrine sweat glands and apocrine sweat glands in the dermis layer of the skin, maintaining the human's thermal equilibrium and excreting metabolic waste^{37,38}. Eccrine sweat contains rich physiological information, including metabolites (glucose, lactate, urea, etc.), electrolytes (Na⁺, K⁺, etc.), nutrients (Vitamin C, Zn²⁺, Ca²⁺, etc.), hormones (cortisol, estrogen, etc.) and proteins³⁹. Four types of wearable optical sweat sensors including colorimetric, SERS, fluorescence, and ECL, have been developed for the analysis of various substances (Table 1).

Colorimetric sensor

Colorimetry attracted many attentions in wearable sweat sensor because its rapid response, portable, multi-channel analysis^{15,40,41}. As chromogenic

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Fig. 1 | Schematic of wearable optical sweat platforms for personalized monitoring. Four types of optical sweat sensors, including colorimetry, surface-enhanced Raman scattering (SERS), fluorescence, and electrochemiluminescence (ECL) sensors.

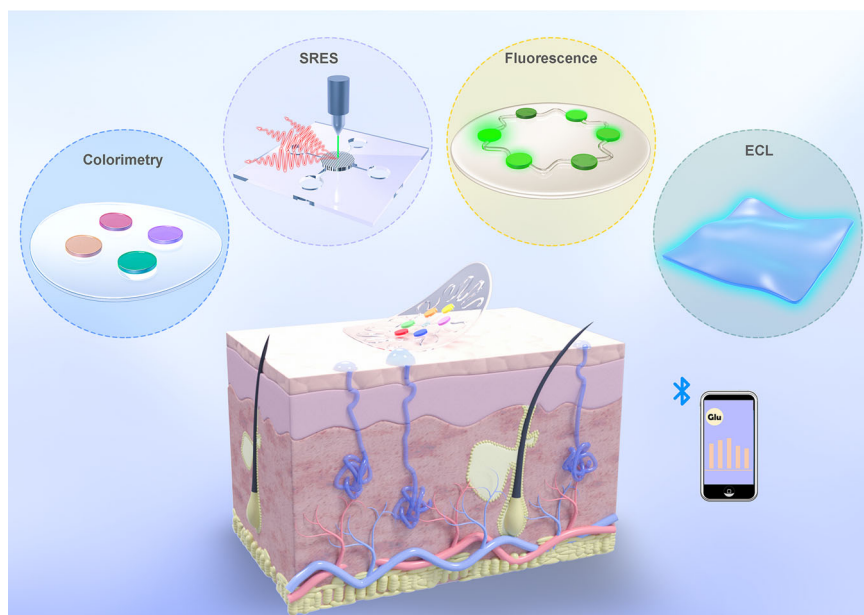


Table 1 | The analytes in sweat and sensing performance in different optical sensors

Analytes	Mechanism	Concentration in sweat (mM)	Detection range (mM)	Response time	LOD (mM)	Refs.
Lactate	Colorimetric	5–40	1.5–100	<60 s	/	15
	SERS		0.01–100	/	/	75
	Fluorescence		1–12.5	/	0.4	89
	Electrochemiluminescence		0.05–20	/	16.7×10^{-3}	34
Urea	Colorimetric	4–12	0–30	/	0.60	109
	SERS		0.1–1000	/	/	75
	Fluorescence		0–40	≈ 300 s	1.4×10^{-3}	90
	Electrochemiluminescence		1–40	/	/	94
Glucose	Colorimetric	0.01–0.2	0.1–0.5	15 min	0.03	62
	SERS		10^{-4} –1	/	1.68×10^{-4}	77
	Fluorescence		0.01–0.25	/	7×10^{-3}	89
pH	Colorimetric	3–8	3–8	15 min	/	55
	SERS		4.25–7.5	/	/	73
	Fluorescence		4.1–6.6	/	/	89
Cl ⁻	Colorimetric	10–100	10–150	/	/	14
	Fluorescence		5–100	/	5	89
	Electrochemiluminescence		1–800	/	/	94
Zn ²⁺	Colorimetric	0.1 – 20×10^{-3}	20 – 100×10^{-3}	1 min	/	65
	Fluorescence		1 – 30×10^{-3}	/	/	33
Mg ²⁺	Colorimetric	0.02–0.4	0.5–5	10 min	/	55
Ca ²⁺	Colorimetric	0.2–2	0.2–3	1 min	/	65
copper	Colorimetric	0.5 – 20×10^{-3}	1 – 3×10^{-3}	/	/	61
Iron	Colorimetric	0.1 – 30×10^{-3}	20 – 100×10^{-3}	1 min	/	65
Vitamin C	Colorimetric	0.01 – 50×10^{-3}	20 – 100×10^{-3}	1 min	/	65
Creatinine	Colorimetric	0.01–0.03	0.0156–1	<1 min	/	15
Cortisol	Fluorescence	0.06 – 0.7×10^{-5}	10–1000 ng/ml	/	2.08 ng/ml	110

molecules interact with target biomarkers, their photon absorption change, consequently leading to alteration in color⁴². Colorimetric sweat sensors mainly operate via chemochromic mechanisms. These mechanisms can be categorized as follows: Electron transfer in redox reactions causes color

changes (for glucose); ions form colored complexes by binding with complexing ligands (for chloride); and halochromism occurs under acidic or alkaline conditions (for pH)^{43,44}. Colorimetric sweat sensors have made substantial innovative advancements in materials, structural design, data

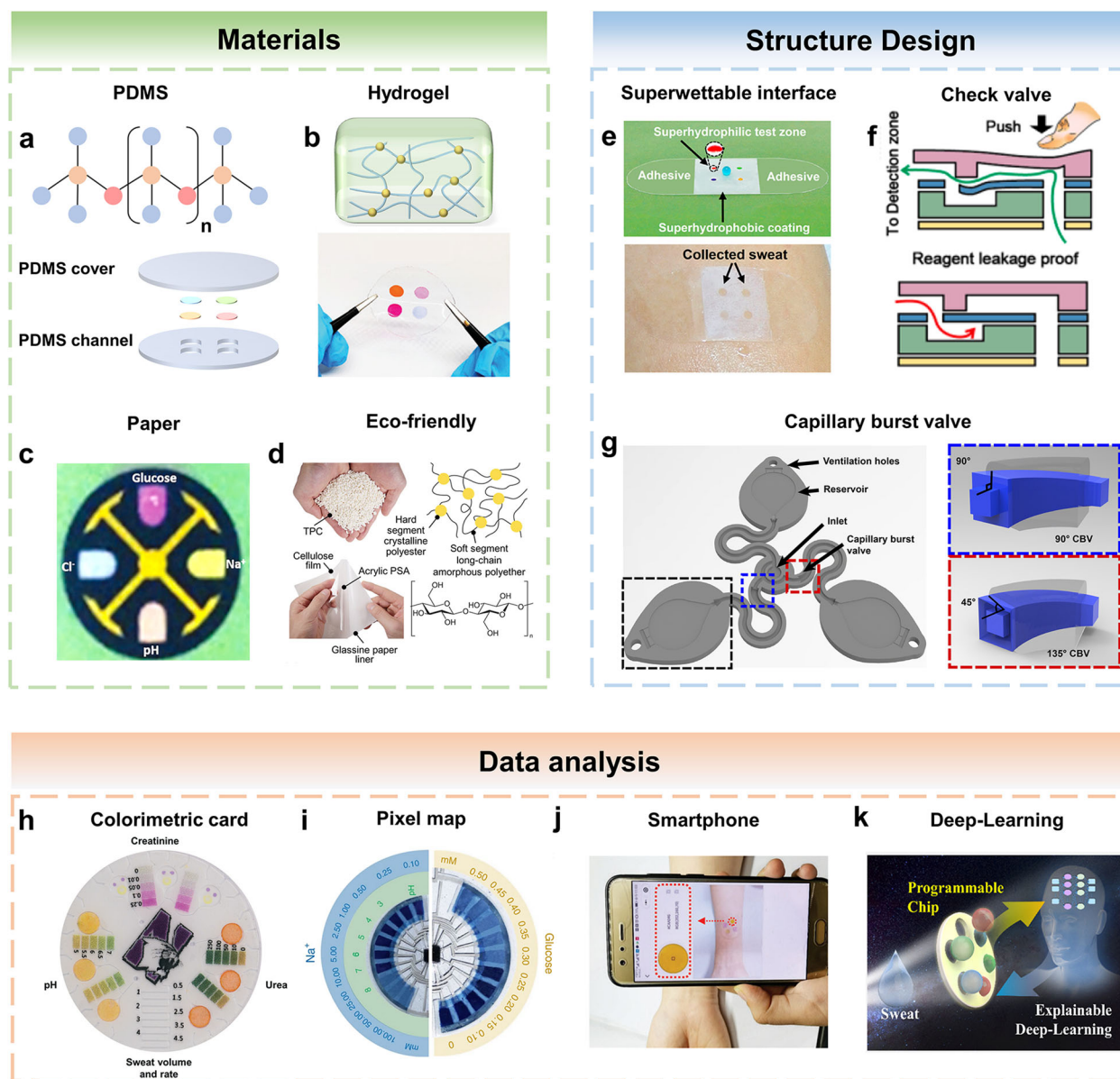


Fig. 2 | Advancement in materials, structure, data analysis of Wearable colorimetric sweat sensor. Common materials in colorimetric sweat sensor: **a** PDMS. **b** Hydrogel. **c** Cellulose paper. **d** eco-friendly. Structure design in colorimetric sweat sensor: **e** Interface modification. **f** Check valve. **g** Capillary burst valve. Data recording and analysis: **h** Standard colorimetric card. **i** Pixel map. **j** Smartphone reading. **k** Deep learning. **b, j** reproduced with permission from ref. 49, copyright 2021, Royal Society of Chemistry. **c** reproduced with permission from ref. 54, copyright 2019, John Wiley and Sons. **d** reproduced with permission from ref. 56,

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analysis. These works enhanced the system sensing performance, efficiency of sweat sampling, wearing comfort, and data accuracy^{31,42,45,46}.

The materials in colorimetric sweat sensors. The materials for wearable sweat sensors need to be conventional biocompatibility, stretchability, flexibility, as well as absorption for biological fluids^{47,48}. Stretchable polymer materials exhibit flexibility, adhesion, and elasticity. For instance, polydimethylsiloxane (PDMS) is widely applied for fabrication of various types of microfluidic chip (Fig. 2a)¹⁴. Hydrogel, a polymer material cross-linked by a three-dimensional polymer network, exhibits exceptional biocompatibility, mechanical properties, hydrophilicity, and water retention, presenting inherent advantages in sweat sensors^{49–52}. Furthermore, its high transparency ensures that colorimetric readings remain unaffected,

enhancing result interpretation. Wang et al.⁴⁹ designed a flexible, self-healing, and adhesive colorimetric hydrogel sweat patch. Colorimetric reagents were incorporated into the polyvinyl alcohol (PVA)/sucrose hydrogel network to enable the comprehensive analysis of sweat components, encompassing pH, glucose, Cl⁻, and Ca²⁺ (Fig. 2b). Sweat patches are mainly disposable products, underscoring the significance of employing degradable materials for environmental considerations. Filter paper, as a naturally degradable cellulose material, renders it a suitable substrate for sweat sensing (Fig. 2c)^{45,53–55}. For commercially viable eco-friendly materials, ref. 56. have engineered a degradable sweat patch comprised of over 90% environmentally friendly components. They devised microfluidic sweat sensor utilizing a commercially available degradable low-modulus thermoplastic co-polyester elastomer (TPC), transparent cellulose

membrane, and green chromophore molecules for detecting the pH and Cl^- in sweat (Fig. 2d).

The structure in colorimetric sweat sensor. Fluid collection is an important sub-function of the sweat patch^{57,58}. The traditional way relies on absorbent materials such as paper, textile, and absorbent pad, but exist some limitations: low efficiency; cross-contaminated sweat, and irreversible color change. Advanced fluid manipulation containing interface modification and microfluidic technology can address above issues^{41,48,54,59}. Superwetable materials, possessing the ability to anchor, drive on-demand, and enrich fluid, are widely applied in sweat management. He et al.⁴¹ reported a superwetable bandage. The superhydrophilic micropores are etched onto the superhydrophobic polyethylene glycol terephthalate (PET) film. Driven by a wettability gradient, sweat is absorbed within functionalized superhydrophilic micropores, impeding its dispersion towards the adjacent superhydrophobic interface. This design greatly enhances the efficiency of sweat sampling and detection (Fig. 2e).

The major challenges (mixing of new and old sweat, backflow of sweat and chemical reagents, no feedback, irreversible detection) exist in colorimetric sweat sensor. Researchers introduced various functional microfluidic chips by proposing a strategy of space compensation for time. Microfluidic devices allow the real-time tracking of sweat loss rate and chemicals level. Through the combined effects of the natural secretion pressure of sweat glands and the capillary forces of microchannels, a skin-interfaced microfluidic patch can promptly collect sweat samples, reducing evaporation and reflux pollution⁶⁰. The finger or sweat pressure actuated pumps and valve structures are equipped to upgrade capabilities of biofluid sampling and analysis, including but not limited to check valves, pinch valves, suction pumps, capillary burst valves, and super absorbent polymer valves^{59,61–64}. Fig. 2f displays a finger-actuated check valve structure⁶². Once the check valve is activated, sweat would be directed into the microfluidic channel, preventing backflow of sweat and chemical reagents to avoid skin contamination. Wu et al.⁵⁹ designed a sweat-actuated capillary burst valve (CBV) structure by 3D printing technology (Fig. 2g). This precision-engineered valve allows sweat to pass through only when it accumulates to a specific pressure (blue: 0.66 kPa; red: 0.86 kPa) and enables the sequential collection of sweat and provides time-sensitive intermittent analysis results.

Data analysis. Data recording and analysis are crucial determinants of sensor performance. Conventional colorimetric quantitative methods include RGB (Red, Green, Blue) analysis⁶⁵ and statistical approaches such as principal component analysis⁶⁶ and hierarchical cluster analysis⁶⁷. A direct, low-cost, efficient and portable way is comparison with standard colorimetric card (Fig. 2h)⁶⁸. In addition, an innovative form of direct data visualized platform, the stretchable electrochromic sweat sensor, is proposed. This work converts the biomarker signal collected by the electrochemical sensor into a digital signal through an analog-to-digital converter, which is then displayed in the form of pixels (Fig. 2i)⁶⁹. Although these direct comparison ways are simple, portable, and fast, they have relatively low resolution. The more objective method for chromaticity sensor analysis involves smartphone-assisted capture of RGB or grayscale values (Fig. 2j)⁴⁹. This is realized through commercially available color analytical software such as ColorGrab and ColorPick, or independently custom-developed software. In general, accuracy of optical data is susceptible to many factors, such as photography frame, ambient light, pH, and component of sweat. With the advancement of artificial intelligence (AI), machine learning, deep-learning are proven to accurately captures multi-dimensional physiological signals in sweat and predicts future trends. Wearable sensors have ushered in smart, automation, and efficiency in data analysis^{70,71}. For example, a deep learning convolutional neural networks (CNN) algorithm is proposed to analyze colorimetric data, and class activation maps (CAM) is employed to elucidate the mechanism of CNN. This method can precisely classify and

quantify four biomarkers in sweat, boasting a match rate of 91.0–99.7% with laboratory test results (Fig. 2k)⁷¹.

In the past few years, colorimetric sweat sensors have gained significant advancement in sensing mechanism (electrolytes, metabolites, ions, hormones, etc.), substrate material (paper, textile, hydrogel, PDMS, etc.), microfluidic structure (pump, tesla valve, check valves, pinch valves, etc.) and data recording (standard colorimetric card, smartphone)⁴². Nevertheless, many challenges still remain in colorimetric sweat sensors, hindering their prospect to achieve high spatial and temporal resolution detection, stability during wearable deformation, and reliable manufacturing at low cost. For future prospective, it is necessary to develop flexible materials with enhanced skin compliance improve comfort and reduce iatrogenic injury upon wearing. Advanced micro-nano manufacturing technologies, such as photolithography, laser etching, 3D printing and digital light processing (DLP), are required to enhance the pump and valve structure of microfluidics^{59,63,64,72}. This enhancement facilitates sweat transmission, reduces evaporation and backflow contamination, and improves detection accuracy.

SERS

When photons are incident with molecules, most of photons scattered elasticity (Rayleigh scattering). The frequency, wavelength, and energy of photons are not change. However, a small part of photons changes frequency, wavelength and energy, which is called inelastic scattering. Raman scattering is an inelastic scattering phenomenon of photons. SERS is a molecular vibrational fingerprint spectroscopy technology with ultra-high sensitivity, label-free, and specificity. Laser excitation of specific rough metal plasmon nanostructure will enhance the Raman signal of analytes by factors of 10^6 to 10^9 , through the localized surface plasmon resonance (LSPR) effect^{32,73,74}. SERS effect is widely applied in biochemical fields. SERS sensors construct on rigid substrates cannot adapt to elastic skin. In recent years, researchers have optimized the sensitivity, uniformity, and stability of SERS substrate materials, achieving flexible and stretchable plasmonic nanostructured SERS substrates^{74–76}. Simultaneously, portable Raman spectrometers are exploited, holding the potential for on-site monitoring and wearable applications of SERS sensor³⁵. Certain target biomarkers are present at low levels in sweat. The inherent advantages of SERS: high sensitivity, trace analysis, and label-free detection, serve to offset the limitations inherent in electrochemical and colorimetric sensor⁷⁷. The integration of flexible plasmonic nanostructured SERS substrates with integrated electronics, builds a link between wearable sweat sensors with SERS.

The materials with SERS effects are limited to nanostructures of gold, silver, copper and a few alkali metals. Researchers synthesize many plasmonic nanostructures around these metals, such as silver nanosnowflakes (AgNSFs) (Fig. 3a)⁷⁸, silver nanowire (AgNW) (Fig. 3b)³², gold nanorods (AuNRs) (Fig. 3c)⁷⁶, core-shell gold nanorods⁷⁹, artificial plasmonic compound-eye (APC) (Fig. 3d)⁸⁰. Wearable sweat analysis platforms based on plasmonic nanostructures are proposed in recent years. Wearable sensors are required to adapt to the deformations during body movements. Plasmonic nanostructures are integrated with flexible materials to form flexible SERS substrates, such as PDMS, silk fibroin, polymethylmethacrylate (PMMA), and electrospinning membranes. Koh et al.³² proposed a flexible silk fibroin film loaded with AgNWs, achieving the absorption of sweat and the analysis of the methamphetamine analog 2-fluoromethylamphetamine (2-FMA) in sweat (Fig. 3e). Subsequently, the flexible microfluidic structure is introduced to establish a stretchable microfluidic SERS system designed for comprehensive sweat management. This microfluidic system demonstrates a capability for achieving high spatial and temporal resolution, enabling simultaneous quantitative analysis of sweat loss, sweat rate, and metabolite concentration in sweat (Fig. 3f)⁷⁶. He et al.⁷⁵ demonstrated a PDMS microfluidic SERS system with high spatial and temporal resolution (Fig. 3g). An innovative and precise plasmonic nanostructure was proposed by incorporating SiO_2 particles into PS microspheres through controlled heating, followed by removal via chemical etching. In practical applications for sweat analysis, researchers designed a

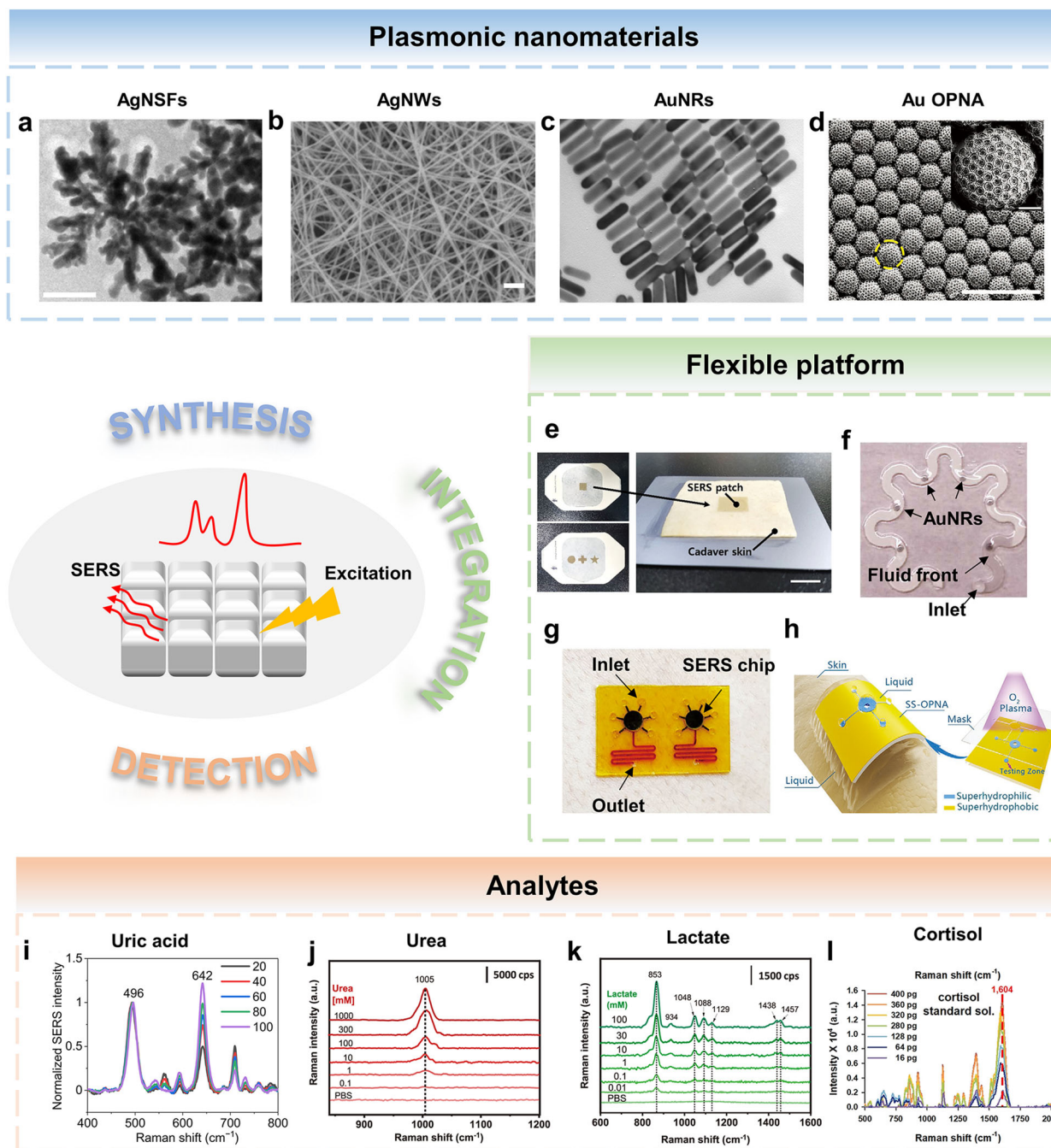


Fig. 3 | Advancement of wearable SERS sweat sensor in plasmonic materials, platform and analytes. Plasmonic Materials in SERS sweat sensor: **a** Ag nanosnowflakes (AgNSFs). **b** Ag nanowires (AgNWs). **c** Au nanorods (AuNRs). **d** Au omnidirectional plasmonic nanovoids array (OPNA). Various wearable SERS sweat platform: **e** A silk fibroin film sweat SERS patch. **f** A plasmonic paper-based microfluidic SERS sweat sensor. **g** A PDMS microfluidic nano-plasmonic sweat sensor with controllable and high temporal-resolution. **h** A wearable SERS sensor

with superhydrophilic/superhydrophobic interface for sweat collection and analysis. Analytes in SERS sweat sensor: **i** Uric acid. **j** Urea. **k** Lactate. **l** Cortisol. **a, l** reproduced with permission from ref. 78, copyright 2021, American Chemical Society. **b, e** reproduced with permission from ref. 32, copyright 2021, American Chemical Society. **c, f, i** reproduced with permission from ref. 76, under the CC-BY 4.0 license. **d, h** reproduced with permission from ref. 80, copyright 2022, Wiley-VCH. **g, j, k** reproduced with permission from ref. 75, under the CC-BY 4.0 license.

superhydrophilic/superhydrophobic interface to autonomously collected sweat, successfully achieving quantitative detection of dopamine (Fig. 3h)⁸⁰. Up to date, the developed wearable SERS sweat sensor has proven the capability to analyze various target substances in sweat, including metabolites (e.g., uric acid, urea, and lactate) and hormone (e.g., cortisol) (Fig. 3i, j)^{75,76,78}. Flexible SERS sweat platforms are also required to collect biofluid. Porous membrane and electrospinning nanofiber can rely on wicking to absorb sweat onto hotspots. However, the drawbacks typically involve structural instability and potential skin contamination upon

contact. Microfluidic chips spatially guide sweat from designed path to hotspots. This refreshable sweat sampling ensures the SERS analysis conducted with high temporal resolution.

Up to date, Wearable SERS sweat sensors, based on diverse flexible plasmonic nanostructures, have been developed for exploring the chemical information in sweat, including drugs, ions, and metabolites. These sensors perform the superiority of label-free, high specificity, and ultra-high sensitivity (single molecule detection). However, it is still inevitable to encounter many challenges. Flexible plasmonic nanostructures are key component of

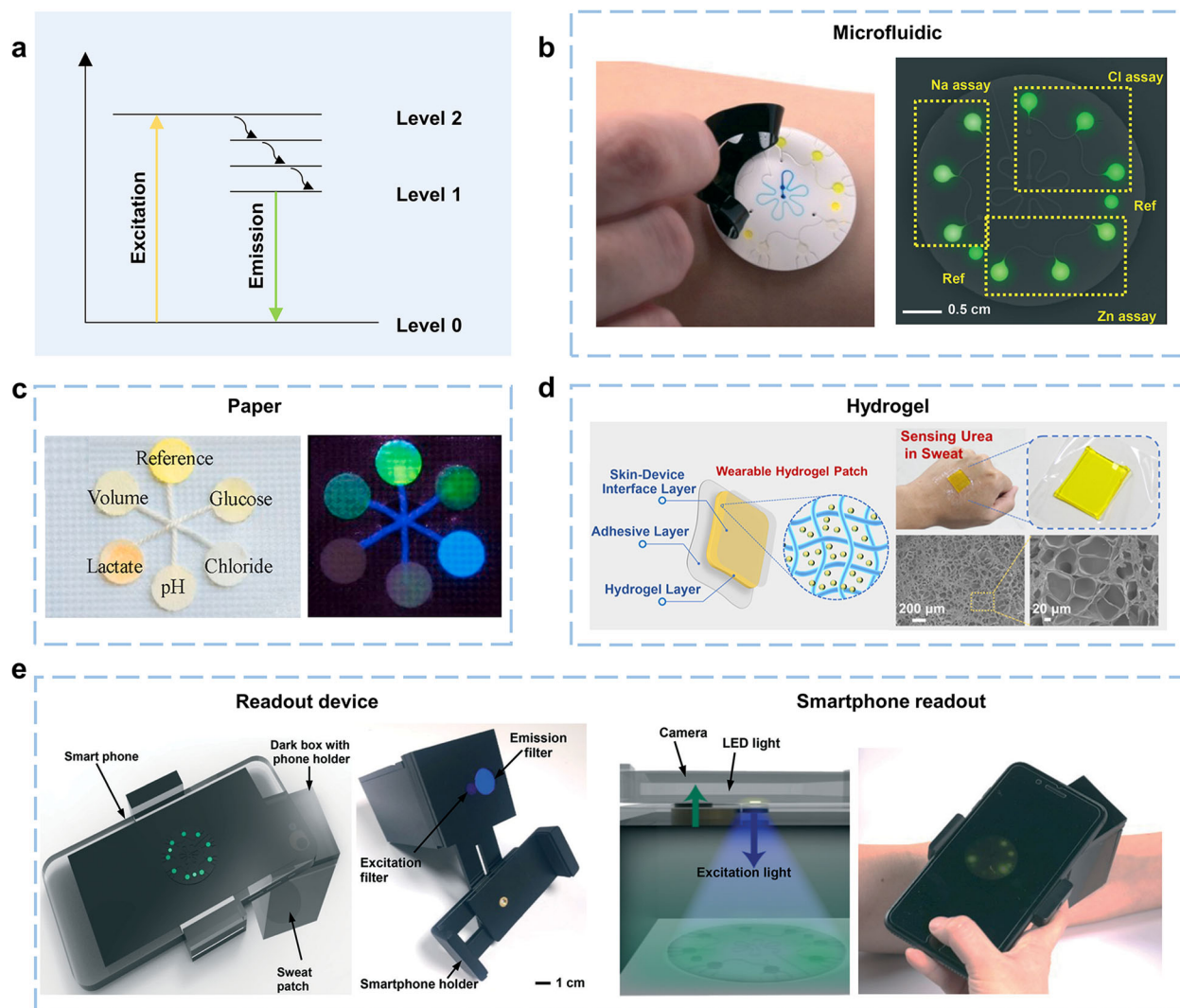


Fig. 4 | Fluorescent wearable sweat sensor. **a** Mechanism of fluorescence spectroscopy. **b** A fluorometric microfluidic patch for in situ sweat analysis and an imaging module. **c** A disposable and low-cost cellulose-based fluorescent sensor. **d** A fluorescent skin-interfaced polyacrylamide hydrogel for sweat urea analysis. **e** Readout device and smartphone readout process of fluorescence sweat sensors.

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SERS sensor, The chemical properties of some SERS sensitive materials are unstable, such as silver nanowires or silver nanocubes^{74,76}. It is not ideal for achieving long-term wearable detection in the environment. On the device side, current portable Raman spectrometers are developed. Although they can perform responsively quantitative and qualitative analysis of solid, liquid, and gaseous samples without pre-treatment, challenges such as low resolution, fluorescence interference, expensive, and high power still exist^{30,75}. On sweat manipulation, fiber membranes, hydrogels, super-wettable materials, and microfluidics are used to sample and transport sweat^{81,82}. Advanced pump and valve structures have not yet been employed in SERS sweat sensor. The high spatial temporal resolution, automatic triggering, and self-feedback is desirable in wearable scenes.

Fluorescence

Fluorescence is a photoluminescence phenomenon. Fluorophore molecules absorb photons when exposed to laser, elevating their energy levels and transitioning to an unstable excited state. It releases energy by emitting fluorescence, returning to a stable ground state (Fig. 4a)^{83,84}. Fluorescent sensors have been applied in medical diagnosis and bioimaging, and made significant progress in healthcare field⁸⁵. In the fluorescence sensor mechanism, a fluorophore probe labeled with target receptor (protein,

nucleic acid, chemical receptor), upon capturing to the target analyte, the fluorophore molecule will change photophysical status, inducing changes in the fluorescence signal emitted by the fluorophore molecules^{86–88}. The fluorescence analytical method are highly sensitive, selectivity and rapidly responsive. With advancement of charge-coupled device (CCD) and complementary metal oxide semiconductor (CMOS) imaging technology, fluorescence sensors have become a possible to analyze targets in complex sweat as a supplementary way. Efforts have been devoted to integrating fluorescence detection into micro-platforms for sweat management (microfluidic, paper-based and hydrogel) to enable point of care testing, equipped with portable devices such as smartphones and laser sources for data readout.

The researchers developed microfluidic channels using PDMS materials and incorporated microchambers containing fluorescent probes with specificity for target analytes present in sweat. The system is equipped with a laser source and a smartphone imaging module to enable swift quantitative analysis of Na^+ , Cl^- , and Zn^{2+} in sweat (Fig. 4b)³³. This work demonstrates the possibilities of fluorescence methods in wearable sweat analysis. Subsequently, a cheaper method was proposed. A cellulose-based fluorescent patch is developed by modifying paper with specific fluorescent probes and incorporating a cotton thread for sweat absorption and guidance, and

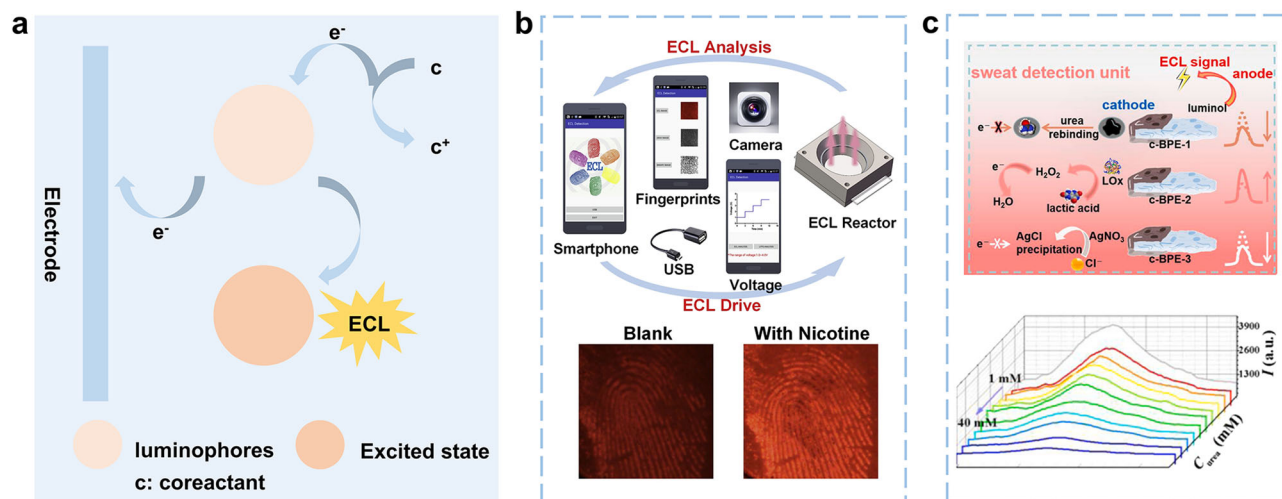


Fig. 5 | Electrochemiluminescent skin-interface for sweat sensing. **a** Oxidation-reduction type in the co-reactant-type ECL mechanism. **b** An ECL fingerprint mapping and finger sweat analysis platform. **c** A luminol-functionalized

electrochemiluminescence hydrogel C-BPE platform. **b** reproduced with permission from ref. 93. Copyright 2019, Elsevier. **c** reproduced with permission from ref. 94. Copyright 2023, Elsevier.

combine with a portable imaging module consisting of UV-LED lamp and filter for data capturing in situ (Fig. 4c)⁸⁹. Since fluorescent hydrogel materials excited at short wavelengths are easily affected by autofluorescence and background fluorescence. In order to reduce the interference, up-conversion nanoparticles (UCNPs) were introduced. UCNPs are special nanoparticles that can convert photons from a low-energy state to a high-energy state. Different with conventional fluorescent probes, it has the characteristics of no background fluorescence interference, strong chemical stability, and long life. Researchers designed a hydrogel fluorescence patch that loaded UCNPs (NaYF₄: Yb, Er/Tm@NaYF₄). This patch enables the rapid detection of urea in sweat, minimizing environmental and skin interference commonly associated with traditional colorimetric sensors. The limit of detection (LOD) has been achieved at 1.4 μM (Fig. 4d)⁹⁰. A high-quality readout system is crucial aspect in fluorescent sweat sensors, requiring lightweight, compactly structured, and economically price. As shown in Fig. 4e, the following components are equipped: laser source for exciting target; dark box for avoiding interference of ambient light; optical filter for removing the background emission; CMOS detector, such as smartphone and photodiodes³³.

Fluorescent sweat sensors have garnered significant attention in wearable sweat sensing research due to their good selectivity and sensitivity. Currently, sweat-associated fluorescence sensors have been explored but still limited. The potential of integration intelligent data acquisition tools with adaptable electronics for fluorescence sensing has been suggested, offering help in analysis and diagnostic applications on wearable sweat platforms^{43,86}. However, the identified analytes in sweat are still commonly confined to glucose, lactate, and typical ions. For further advancements in sweat monitoring, more fluorescence probes of metabolites and proteins require to be developed. In readout device, the necessity for an integrated laser source and imaging system presents an inevitable challenge, constraining the exploration of existing wearable fluorescent sweat patches. The introduction of new smart integrated imaging devices and customized decoding software is necessary to enhance the potential of noninvasive fluorescence sweat sensors, generating greater value to these innovative sweat patches.

Electrochemiluminescence

Electrogenerated chemiluminescence or electrochemiluminescence (ECL) is an electrochemical-photophysical process in which an electrochemical reaction occurs near the electrode surface to generate excitons and radiate light. The ECL mechanism includes annihilation mechanism and co-reactant mechanism. In the annihilation ECL mechanism, the luminophore

undergoes direct electron transfer, either oxidized at the anode or reduced at the cathode under potential control, thereby generating luminophores in excited or ground states. In co-reactant mechanism, the substance within the system undergoes electrolysis, transitioning into an oxidized or reduced intermediate through the application of an electrical signal to the electrode. Subsequently, the intermediate engages in a further reaction with the oxidized or reduced co-reactant, becoming an unstable excited state. Once a substance returns from its excited state to ground state, it emits an optical signal (Fig. 5a)^{91,92}. There is no need of external light source on ECL-based detection methods. ECL presents notable advantages, including ultra-low background noise, high sensitivity, and multi-dimensional signal extraction. It holds substantial promise for applications in wearable light-emitting devices, fibers, representing expansion of electrochemical and optical based wearable sensing devices. At present, there are few reports related to sweat sensor based on ECL method, indicating substantial potential for future development in expanding analyte detection and manufacturing flexible devices. Li et al.⁹³ used ECL technology and smartphone-assisted imaging to achieve optical fingerprint mapping, and sensing of nicotine and TNT in sweat on finger (Fig. 5b). Huang et al.³⁴ introduced a pathway in wearable sweat sensor by developing a flexible and stretchable ECL sensing film. They immobilized highly luminescent nanospheres (HLN), based on [Ru(dcbpy)₃]²⁺, onto gold nanotube (AuNT) electrodes fabricated on a flexible PDMS substrate. Employing molecular imprinting principles, they achieved in-situ detection of lactate and urea in sweat. The closed bipolar electrode (C-BPE) represents a distinctive electrode configuration, wherein, under the polarization of an electric field, one end of the conductor functions as the anode, undergoing oxidation reaction, while the other end serves as the cathode, undergoing reduction reaction. Due to the absence of a direct wire connection between this electrode and an external power supply, the challenge arises in reading the electrical signal. Consequently, the electrochemiluminescence method emerges as a practical solution to interpret the redox signal present on the electrode surface. Li et al.⁹⁴ proposed a hydrogel-based C-BPE sensing system. In this system, a reduced graphene oxide (rGO) hydrogel functions as the cathode, while a luminol-functionalized hydrogel serves as the anode. Upon absorption of sweat, the hydrogel undergoes swelling, initiating a spontaneous healing process at both the cathode and anode interfaces, thereby forming a functional C-BPE sensing system. Subsequently, the oxidation-reduction intensity of the cathode is assessed based on the luminous intensity of the anode. This integrated platform facilitates the detection of urea, lactate, and Cl⁻ in sweat (Fig. 5c).

The application of ECL in wearable sweat sensors remains limited. While integrated electrochemical devices have been successfully developed,

Table 2 | Advantages and disadvantages of sweat sensors with different mechanism

Mechanism	Advantages	Disadvantages	Refs.
Colorimetric	Low cost light weight Easy to mass produce Good selectivity	Irreversible Discrete data Poor sensitivity Poor temporal resolution	49, 63, 111
SERS	Lable-free high sensitivity and selectivity Low-volume analysis	Require Raman spectrometers Not suitable for long-term monitoring Repeatability Expensive	36, 75, 76
Fluorescence	Good sensitivity Good selectivity Rapid responsive	Require laser source Ambient light interference Relatively narrow range of detectable targets	33, 89
Electrochemiluminescence	Good sensitivity and selectivity	Complicated circuits Ambient light interference	34, 94
Electrochemical	Real time and continuous detection Rapid responsive Good selectivity and sensitivity High temporal resolution	Complicated circuits Power supply Relatively expensive	24, 98, 112

there is a pressing need for future advancements to focus on the incorporation of flexible conductive materials, ECL materials, expansion of target analytes, enhancement of biosafety measures, and the integration of imaging capabilities. In data reading, its readout device bears similarity to a fluorometric sweat sensor, yet it operates independently of an external light source. This characteristic mitigates background fluorescence interference, enhancing accuracy. A concerted effort towards these aspects holds the potential to significantly advance the application of electrochemiluminescence in the realm of wearable technology.

Engineering efforts in optical sweat sensors

Engineering efforts propel epidermal optical sweat systems into commercialization. The colorimetric and electrochemical sweat patches pioneer production in sweat analytical devices due to their advantages of low cost, easy mass production^{95,96}. Epicore Biosystems as a company has centered mainly on the advancement of “skin-like” flexible microfluidic sweat solutions that enable non-invasively analyzing sweat physiological information in-real time. The Gx Sweat Patch, a colorimetric sweat sensing patch, is developed by Epicore Biosystems in joint with PepsiCo and Gatorade. This soft patch manufactured using the roll-to-roll process collects sweat through two microchannels during exercise, and provides real-time sweat rate, Cl⁻ level, and individualized recovery insights. The sport performance and sweat physiological information of 312 athletes have been investigated, and the data obtained supports the development of reliable algorithms and personalized feedback⁷². Flexible microfluidics, roll-to-roll, laser engraving, screen printing manufacturing processes, big data, and other engineering efforts, encouraging the combination of bioelectronics and biochemical sensor modules in fully-integrated, low-cost, and mass manufactured epidermal optical sweat systems.

Outlook

Wearable optical sweat sensors have developed several years, boosting the upgrade of optical skin-interfaced sensor based on diverse mechanism and functionalities^{33,39,40,94,97}. As shown in Table 2, different from electrochemical sweat sensor, colorimetric sweat patches are more portable, compact, and

low-cost, due to avoiding complex circuits (for data acquisition and transmission)^{59,98–101}. Wearable SERS sensors hold irreplaceable advantages: lable-free, high specificity, and good sensitivity (single molecule detection). The limitations are that they require coordination with specialized Raman spectrometers, which increases inconvenience of long-term monitoring and available cost⁸². Wearable fluorescence and electrochemiluminescence sweat sensors based light emission, have highly selectivity and sensitivity. These sensors require complementary accessories to acquire optical signal (laser source, electronic circuits), bring a highly power consumption during long-term monitoring. Light emission-based sensors can also be easily affected by ambient light such as sunlight, and require dark box to capture exact light signals^{30,96}.

Optical sweat sensors build sensitive, economic, and non-invasive platforms for healthcare, including various nutrition, metabolisms, electrolytes. Currently, while colorimetric sweat devices have been gradually commercialized, other types remain in the laboratory stage⁷². As for the prospective of sensing materials in optical sweat patches, more abundant target analytes within sweat such as protein, hormone need to be explored. The optical sensing then should fulfill the demands of sensitivity, specificity, accuracy, and reproductivity. Thus, more potential probes for optical sensing and enhanced signal need to be exploited. sweat patches are mostly disposable items, biodegradable material, and recyclable reagents is necessary to reduce the environmental impact of discarded components. For example, TPC can replace commonly used silicone elastomers, such as PDMS, Ecoflex; Natural product anthocyanins for pH detection⁵⁶. Considering the wearing comfort and skin compliance, demand for flexible and stretchable materials is crucial to prevent discomfort and potential injury, particularly during long-term wear^{47,102}.

On sweat manipulation, combining with absorbent materials (paper, textile, hydrogel) and advanced sweat control and feedback system (microfluidics and superwetable interface), is capable of addressing limitations such as low temporal resolution, reagent backflow contamination, and sample evaporation in optical sensors. The precise pump and valve structures that can achieve finger or self-driving, self-feedback, temporal, and quantitative detection, are manufactured using advanced micro-nano techniques, including photolithography, laser etching, 3D printing, roll-to-roll (R2R) and digital light processing (DLP)^{24,42,103–105}.

On data readout and analysis, optical sweat sensors need to collaboration with external devices for data reading. Apart from standard colorimetric card and smartphones, external laser sources (fluorescence), portable Raman spectrometers (SERS), and electronic circuits (electrochemiluminescence) are needed. In addition to conventional curve fitting, the integration of machine learning and artificial intelligence are demand to employed to precisely analyze, calibrate, and predict data. The future trend is to amalgamate these methodologies with big data platforms, ultimately achieving personalized diagnosis and precision medicine^{101,106–112}.

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Competing interests

The authors declare no competing interests.

Additional information

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