

Review

Recent Advances in Wearable Sensors for the Monitoring of Sweat: A Comprehensive Tendency Summary

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Abstract: Sweat, as a biofluid that is easy to extract and contains a variety of biomarkers, can provide various types of physiological information for health monitoring. In recent years, research on wearable sensors for sweat sensing has been emerging continuously. Wearable sweat sensing will probably become an alternative method to traditional chemical analysis. This is due to its advantages of portability, non-invasiveness, comfort, and continuous monitoring. Since the inception of this research field, wearable sweat sensors have achieved significant development in terms of materials, structures, systems, and application directions. Research interests are gradually evolving from single biomarker detection to the pursuit of multi-channel, multi-modal system-level architecture. The analysis of physiological signals has also developed from single signal characterization to omics analysis using multiple physiological information sources. Based on the changes mentioned above, this paper mainly introduces the latest researches of wearable sweat sensors from the aspects of strategy, architecture, material, system, data processing, etc., and tries to summarize the trends of sweat sensors. Finally, this paper analyzes the challenges faced by the sensing platform and possible methods for optimization.

Keywords: health monitoring; sweat analysis; wearable device; sensing platform; non-invasive detection



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1. Introduction

In the last few years, there has been an increasing focus on personal health and disease prevention. Monitoring human physiological signals is a crucial approach to achieving this goal. One common situation is that individuals often experience discomfort or specific symptoms prior to seeking medical attention, which can result in delayed treatment. Traditional detection techniques typically depend on trained professionals, numerous sample extractions, complex and expensive instruments, and lengthy sample analysis durations. Moreover, these techniques are often invasive and rely upon subjective diagnostic results from healthcare professionals. As such, they may be inadequate to meet the growing demand for convenient and accessible detection. In contrast, wearable sensors offer several advantages, including portability, low cost, comfort, and non-invasiveness. These devices enable in situ detection and wireless data transmission, overcoming many of the limitations of traditional methods. Therefore, wearable sensors have the potential to serve as an alternative approach to detection and have attracted significant research interest. So far, both physical and chemical sensors have made notable advancements [1–3]. Wearable chemical sensors are capable of detecting a wide range of biomarkers, such as metabolites, nutrients, drugs and so on. Through the use of transducers and data analysis, these biomarkers can be converted into practical information for use in various scenarios,

including daily life, sports performance, clinical diagnosis, and rehabilitation. Biomarkers exist in a wide range of biofluids, e.g., blood, interstitial fluid, sweat, tears, saliva, etc. Blood has always been the gold standard for biochemical detection, while other non-invasively accessible biofluids also contain many of the same components as blood. Thus, interstitial fluid, sweat, tears and saliva have become the primary target biofluids for wearable sensors. Many studies on tear monitoring have utilized contact lenses for glucose detection, which may cause discomfort for the wearer [2]. The composition of saliva is highly similar to that of blood, and sample extraction is relatively simple. However, a disadvantage of saliva monitoring is that it is difficult to deal with the noise interference introduced by eating and the oral environment [4]. Conversely, sweat is easy to extract and the sample is less disturbed by the environment. It also contains similar biomarkers to blood, including metabolites, electrolytes, proteins, hormones, and micronutrients. Consequently, there are compelling reasons to use sweat as a complementary tool for standard analytical diagnosis [5], and sweat sensors have always been a popular area in the field of wearable biosensor research. Since Gao et al. published their fully integrated sweat sensor [6], many wearable sensors with different shapes and principles have emerged, including tattoos, wristbands, patches, and rings [7]. After several years of development, the focus of wearable sensor research has shifted significantly from its initial direction. Wearable sensors were initially designed to simply capture and process signals produced by the human body. However, these devices are now increasingly focused on biochemical analysis to obtain more detailed information about health conditions and are utilizing omics research to provide a more comprehensive picture of human health. Regarding sensor structure and fabrication, with the development of flexible electronics, research has focused more on sensing materials, structural design, and system integration to achieve multichannel and multimodal sensing. This article focuses on showing the latest research results in the field of wearable sweat sensors, according to their classification of applications, strategies, morphology, materials, structures and challenges, respectively, and by giving examples of the latest specific research in recent years, in order to summarize the development trend of wearable sweat sensors in recent years. First, the new sweat sensors for different target analytes are introduced according to the application scenarios, which mainly serve as an overview. Then, several modification methods of sweat sensors are discussed. The next section explains the detection strategy used in sweat sensors and some purposeful optimization research. After that, the development of sweat sensor forms and the latest trends are analyzed by introducing innovative progress in materials, structure and systems. Subsequently, the current application of machine learning in sensor signal processing is introduced. Next, challenges and potential feasible solutions in the current sweat sensor research are listed. The last section summarizes the full article.

2. Target Analytes/Application Scenarios for Sweat Sensor

The main components of sweat are ions/electrolytes, small molecules (ethanol, cortisol, urea, lactic acid, etc.) and proteins (neuropeptides and cytokines) [8]. The choice of target analyte for a sweat sensor is determined not only by the application scenario, but also by reference to existing physiological studies.

2.1. Biochemical Analytes

2.1.1. Metabolites

Glucose: Enzyme-based glucose sensors have advanced from the first generation (electron transfer based on hydrogen peroxide involved in redox reactions) to the second generation (media-based electron transfer) [9], and the third generation (electron transfer directly between the enzyme and the electrode without any mediator) [10]. Since the first media-based amperometric sensor [11] was reported, the second generation of glucose sensors have made great progress, but they still have the disadvantages of relative toxicity, solubility of the medium and insufficient system stability [12], which has driven the birth of the third-generation glucose sensor. In the field of wearables, each generation of sensors

is currently being applied, and the second and third generations are more prevalent, mainly used in the management (prevention, screening, detection and treatment) of type II diabetes [13].

Lactate: Lactate reflects metabolic, renal and cardiorespiratory health. During exercise, sweat lactate concentration increases with blood lactate concentration [14], so sweat lactate testing can replace blood testing to some extent. Lactate dehydrogenase (LDH) or lactate oxidase (LOx/LOD) are commonly used for selective identification, and the addition of Prussian blue [9] (a good electron transfer medium) for lactate detection can reduce the reaction potential and improve selectivity [15–20].

Alcohol: Sweat alcohol concentration correlates with blood alcohol concentration [21] and blood ethanol content (BAC) can be determined by detecting transdermal alcohol concentration (TAC) using wearable sweat sensors [22]. Not limited to liquid phase testing, alcohol detection can take advantage of alcohol's volatility. Khemtonglang et al. [23] built a smart wristband for sweat alcohol detection based on an MOX gas sensor, which can detect drunk driving with 94.66% accuracy and can integrate an IoT-based alarm system to facilitate law enforcement.

Cortisol: Cortisol is a glucocorticoid whose concentration in sweat is associated with changes in psychological or physiological stress and is regulated by the HPA axis [24]. Cortisol secretion can help the body maintain homeostasis, but excessive secretion can lead to disease (depression, anxiety, etc.), so real-time monitoring is necessary. Common detection methods include antibodies, DNA aptamers, and molecularly imprinted polymers (MIPs) [25]. Torrente-Rodriguez et al. [26] developed a wearable portable sensing platform for the real-time monitoring of sweat cortisol dynamics, and reported the first cortisol diurnal cycle and dynamic stress response curve constructed by human sweat according to the monitoring results (Figure 1a). Compared with the subjective stress monitoring method of a traditional questionnaire survey, it provides a data-based non-invasive real-time stress monitoring method, and demonstrates the good correlation between the hormonal circadian cycle and stress curve, which is helpful for further improving stress-management methods.

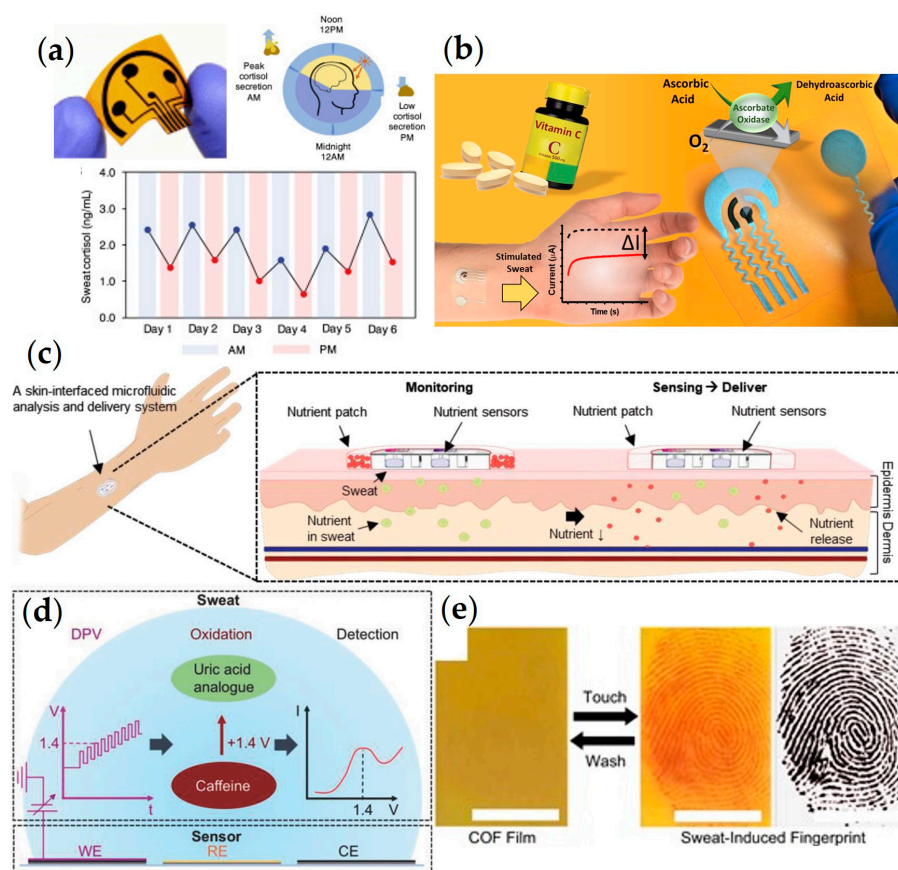


Figure 1. Novel wearable sweat sensors for multiple analytes. (a) A novel cortisol sensor and circadian rhythm study. Reprinted from ref. [26], Copyright (2020), with permission from Elsevier. (b) An enzymatic biosensor that monitors vitamin C in sweat. Reprinted from ref. [27], Copyright (2020), with permission from American Chemical Society. (c) A sweat sensor that monitors multiple nutrients simultaneously, allowing for nutrient replenishment. Reprinted from ref. [28] Copyright (2021), with permission from John Wiley and Sons. (d) Sweat sensor to detect methylxanthine drugs (caffeine) using differential pulsed voltammetry. Reprinted from ref. [29] Copyright 2018, with permission from John Wiley and Sons. (e) A sweat-sensing patch for fingerprint liveness detection measurement. Reprinted from ref. [30], Copyright (2023), with permission from Springer Nature.

Electrolyte: Electrolyte concentration can reflect body fluid homeostasis, and monitoring sweat can help ensure timely replenishment and prevent excessive loss. Electrolytes can be measured through electrochemical methods using ion-selective electrodes or colorimetric methods, with specific strategies tailored to their needs. Among the common electrolytes, sweat chloride can reflect cystic fibrosis, so detecting chloride concentration has been studied for a long time [31]. Zinc ions are early diagnostic biomarkers for muscle stress and fatigue [32] and play a critical role in gene expression and immune function [33]; magnesium ions are essential cations for central nervous system function [34], are involved in neuroendocrine metabolic processes, and can reflect stress levels and sleep status [33]. The detection of these ions can be achieved using sweat-sensing patches [35]. Sodium ion concentrations vary greatly during sweating [36] and Hashimoto et al. used this to propose a real-time colorimetric sensor that expresses electrolyte concentration changes in sweat using sodium chloride as the reference analyte [37]. In the field of electrolyte detection, there have been many studies based on sodium and potassium ions, such as a wearable platform reported by Porvano et al. [38] that can simultaneously detect sodium and potassium ions in sweat, and can detect other target ions by swapping components.

Changes in pH are associated with many diseases or abnormalities, including infection, asthma, diabetes, kidney disease, lung disease and heart disease. pH sensors mostly use potentiometric methods for signal measurement [39–41].

2.1.2. Biomolecules

Amino acid: Amino acids can be used to synthesize proteins, which are vital nutrients for the functioning of the immune and nervous systems. Additionally, proteins contribute to muscle and bone growth and are fundamental substances for human life activities. Yang et al. [42] proposed a wearable sweat sensor for uric acid and tyrosine. It can detect exercise performance after protein ingestion and determine the presence of gout through sweat analysis after the ingestion of purine-rich foods. The results can also be correlated with serum measurements in healthy subjects and ventilated patients. Further research could extend the sensor's capabilities to detect cardiovascular disease, type II diabetes and kidney disease.

Vitamin: As essential micronutrients, vitamins generally cannot be produced by the human body and must be obtained through a sensible diet. Take vitamin C, for example, which can boost immunity, promote iron absorption and, if not consumed in sufficient quantities, can lead to iron deficiency anemia, weakened immunity and even scurvy. Sempionatto et al. [27] reported an enzymatic biosensor for the detection of vitamin C in sweat, which holds promise for the detection of nutrient levels and the provision of personalized nutritional solutions (Figure 1b). Ascorbate oxidase (AAOx)-based printable tattoo electrodes used in the device are highly selective and support the detection of real-time changes in vitamin C for timely assessment of vitamin intake and dietary changes.

Wang et al. [43] designed a wearable electrochemical sensor that continuously monitors amino acid and vitamin levels in sweat. The sensor can assess the risk of metabolic syndrome by correlating amino acid levels in serum and sweat, thus facilitating the adjustment of nutritional health status.

After assessing nutritional levels, further supplementation may be necessary. In addition to improving dietary habits and taking oral supplements, the integration of a nutrient release function into the sensor, similar to a drug delivery module, could also be considered. Kim et al. [28] reported on a miniature sensor system targeting several essential nutrients (vitamin C, calcium, zinc and iron) in sweat and verified the dynamic correlation between the concentration of these nutrients in sweat and the corresponding concentration in blood based on human study results (Figure 1c). During the wearing period, nutrients can also be continuously delivered to the body through transdermal patches that are directly integrated with microfluidic structures. Once colorimetric results indicate a nutrient imbalance, the block layer can be removed to initiate the release process. The efficiency of the drug delivery module has been verified and is comparable to that of oral administration.

2.1.3. Hazardous Substances/Drugs

Drug testing is important for stimulant control and precision medicine, and sweat is an attractive biofluid that holds promise as an alternative to traditional invasive (blood draw) assays [29]. The sweat sensor proposed by Tai et al. [29] in 2018 used differential pulsed voltammetry to detect methylxanthine drugs like caffeine (Figure 1d). The device's ability to measure caffeine levels under different conditions can greatly assist clinicians in adjusting dosages, monitoring patient compliance and understanding pharmacokinetics.

Nicotine is a highly addictive drug and excessive use can lead to heart, brain and respiratory disease, and even lung cancer [44]. Conversely, studies of nicotine in the treatment of disease have also shown that NIC can be used to treat ulcerative colitis, Alzheimer's disease and Parkinson's disease [44]. Based on the above applications, Magesh et al. [45] developed an electrochemical sensor based on MXene ($\text{Ti}_3\text{C}_2\text{T}_x$)/palladium hydroxide-supported carbon (Pearlman's catalyst) composite (MXene/ $\text{Pd}(\text{OH})_2/\text{C}$) to

detect nicotine levels in human sweat. The sensor was validated using sweat samples from smokers and can achieve high sensitivity and selectivity.

2.2. Physical Indicators

2.2.1. Sweat Rate

Sweat rate monitoring is important for screening for physical abnormalities such as hyperhidrosis, thermoregulatory and heat stress-related disorders, mental stress and neurological disorders, and to help prevent dehydration and heat stroke. Sweat rate can be measured using colorimetric (detecting the amount of sweat) and flow methods. Apart from the traditional methods of measuring sweat rate (described above), many new ideas have been developed recently. Kwon et al. [46] used a thermal actuator and thermistor-based system for flow measurement, requiring only a short straight channel for measurement. Hashimoto et al. [37] chose to direct sweat through a short microfluidic pathway in the form of droplets for easy quantification. Momose et al. [47] did not use flow to measure sweat rate, but integrated a capacitive humidity sensor into a ventilation capsule for monitoring. Dautta et al. [48] converted flow to admittance, using the change in admittance when the electrode comes into contact with sweat to measure flow. After the sweat enters the spiral microfluidic channel embedded in the electrode, the admittance value increases as the contact area grows, and the real-time change in sweat rate can be obtained from the admittance data over time. The article also mentions that the real-time monitoring of sweat rate using wearable devices can also help study the relationship between local and systemic sweat rate.

Heat stroke has become a serious global problem. Children, the elderly and manual laborers are particularly susceptible to heat stroke in hot and humid weather. Timely hydration and cooling can effectively reduce the risk of heat stroke. Based on the study of the original sweat meter [49,50], Momose et al. [47] developed an early warning system for the risk of heat stroke using a portable sweat meter. In addition to capacitive moisture sensors, a smartphone-based warning system was developed. The system can provide an early warning of heat stroke risk at the time when the sweat rate changes from negative to positive in the second order, and remind the wearer to rehydrate according to the sweat volume.

The measurement of athletes' physiological data in training relies on accurate, real-time monitoring. While monitoring exercise performance in a laboratory environment requires wired connections and computer analysis, wearables enable non-invasive, continuous sensing and wireless data transmission. Measurements from wearable sweat sensors promise to provide a real-time reflection of an athlete's physical condition, preventing injury, dehydration or cramps, while helping healthcare professionals/coaches tailor hydration, nutrition and rehabilitation programs to each athlete [51]. The quest for lightness and comfort in wearable sports devices has led to a focus on simplifying sensor structures. For example, Liu et al. [52] developed a paper-based sweat sensor using pH and H₂O₂ test strips to meet the needs of sports scenarios. The colorimetric patch sensor has a simple, lightweight, and thin structure, as well as a low cost and strong stretchability. Its minimal impact on human activities makes it suitable for monitoring in motion. Additionally, dynamic sweat measurement can be achieved by integrating smartphone image processing.

2.2.2. Fingerprint

Early studies have used sweat pores to reflect fingerprint patterns to facilitate fingerprint analysis and pore-dysfunction diagnosis; for example, Lee et al. [53] used water-induced materials to reflect sweat pore distribution. More recent work in this area includes the development of a covalent organic framework for live fingerprint detection by Hao et al. [30]. This framework can distinguish human fingerprint patterns based on sweat response and is unresponsive to artificial false fingerprints (Figure 1e). This study exploits the essential difference between living and fake fingerprints, i.e., the secretion of sweat. Sweat hole detection by materials is used to complete biometrics, eliminating the need for

complex feature extraction algorithms used in previous recognition steps [54–58]. This approach is expected to improve the reliability and security of existing fingerprint-recognition technologies. The material can be re-used with ethanol cleaning, ensuring practicality and reusability. Sweat biomarkers have also been mentioned as potentially useful for determining biological age [59].

Table 1 provides a list of common target analytes in sweat and their intended applications. Although the discussion above is separated by different biomarkers, current wearable sweat sensors are often not designed for a single biomarker. A significant number of them also detect body temperature, heart rate, gait, and other indicators simultaneously. This is because the physical state of human body is related to numerous metabolites and small molecules. It is clear that testing each biomarker individually is not as efficient as simultaneously detecting multiple indicators to characterize health status. At the same time, advances in wearable sensor technology allow for the further expansion of device detection capabilities. Multiplex detection also enables the discovery of unknown biomarkers associated with specific pathological conditions.

Table 1. Common target analytes in sweat and related diseases or applications.

Category	Analyte	Target	Applications	References
Biochemical analyte	Metabolites	Glucose	Preventing and treating type II diabetes	[13]
		Lactate	Checking metabolic, kidney, and cardiopulmonary health	[9,14]
		Alcohol	Detecting drunk driving	[21,22]
		Cortisol	Measuring stress changes to prevent depression and anxiety	[24,26]
	Electrolyte	pH	Maintaining human fluid homeostasis, detecting cystic fibrosis (CI)	[35–38,60]
			Checking for infection, asthma, metabolism, pH balance, and wound healing	[39–41]
			Demonstrating exercise performance after protein intake, detecting gout and cardiovascular disease	[28,42]
			Revealing the level of human nutrition, reminding subjects to supplement in time to maintain immunity	[27,28]
	Biomolecules	Amino acid	Helping doctors adjust dosage, observe prescription adherence, and understand pharmacokinetics	[29]
		Vitamin C	Revealing the risk of heart, brain and respiratory diseases, and even lung cancer	[44,45]
Physical indicators	Hazardous substances or drugs	Caffeine		
		Nicotine		
		Sweat rate	Avoiding dehydration and heat stroke, detecting mental stress and neurological disorders, and improving athletic performance	[46,47,51,52]
		Fingerprint Age	Biometrics	[30,53] [59]

3. Modification of Sweat Sensors

3.1. Antibody

Electrochemical immunosensors detect target analytes through the specific binding of antibodies to antigens. In recent studies, immunosensors were commonly used to detect cortisol levels in sweat. Cortisol, as an antigen, interacts with antibodies and inhibits electron transfer, thereby reducing the current response [61]. Santiago et al. [62] adopted this principle to characterize different sweat cortisol concentrations using cyclic voltammetry.

3.2. DNA

DNAs commonly used to modify electrodes include single-stranded DNA (ssDNA) and DNA-based molecular pendulums. The former is specifically identified using DNA

hybridization or signal probe displacement. The latter uses specific binding to target molecules to induce changes in shape and probe electrode spacing to produce recognition signals [63]. When the analyte binds to the DNA on the electrode, the structure and dynamics of the electrode change, affecting the efficiency of electron transfer [64]. DNA-modified electrodes employing electrochemical impedance spectroscopy can provide the continuous real-time detection of cortisol [65].

3.3. Artificial Receptors

3.3.1. Aptamer

When binding to the target molecule, the aptamer undergoes a conformational conversion. When bound to the electrode, the aptamer's identification process causes electron transfer, resulting in a current response. The molecular structure of the aptamers affect the current response, and the distribution density of the aptamers also affects sensor performance [66]. Singh et al. [67] developed a pseudo-junction aptamer-based microfluidic sensor. Through multiple comparative experiments on different aptamers with different hybridization regions, they identified a pseudo-knot aptamer with high sensitivity and low variability. However, aptamers attached to sensing electrodes are not completely stable because sweat contains a small amount of DNase-I, which can degrade aptamers with long-term exposure [68,69]. Surface sealants such as actin and 2ME are widely used to inhibit the activity of DNase-I [70,71]. This study verified the protective effect of 2ME + actin on aptamers.

3.3.2. Molecularly Imprinted Polymer

Molecularly imprinted polymers (MIPs) are specific receptors formed by combining functional monomers with imprinted molecules to form a polymer and then dissociating them, which is widely exploited in biochemical sensing due to its high sensitivity and selectivity. However, the classical MIP structure requires washing after use, which makes it difficult to reuse and can be detrimental to continuous sensing. Wang et al. [43] incorporated functional groups into the polymerized structure of laser-engraved graphene (LEG) after the polymerization of functional monomers to obtain a renewable special acceptor that can be regenerated after binding to amino acids at a constant potential applied by the working electrode.

The lifespan of such sweat sensors is largely determined by the adhesion duration and the activity of the modifier. Therefore, numerous studies have focused on two areas: developing more stable attachment methods to prevent modifier detachment in liquid environments, and designing modifiers that can be regenerated and slow the rate of activity loss. The ultimate goal of these studies is to reduce the frequency of sensor replacement and increase the duration of a single usage.

4. Sweat Sensing Strategies

Typical wearable sweat sensors can be divided into electrochemical and optical sensors. In the last few years, devices using other methods have also been developed.

4.1. Electrochemical Sensing Strategies

The advantages of electrochemical technology are high selectivity, high sensitivity, rapid response, small sample requirements and reproducibility. Electrochemical methods combined with electronic systems can convert biomarker concentrations into electronic signals to accurately quantify physiological parameters. Electrochemical methods are used not only in measurement but also in device characterization.

4.1.1. Potentiometric Sensing

Potentiometric sensors are based on the Nernst equation and measure the electrolyte concentration using the potential difference between the reference electrode and the working electrode [1]. The target of potentiometric sensors includes diverse ions and the working

electrode is ion-selective. During selective ion identification, a potential change is induced and converted into a voltage signal by the transducer.

4.1.2. Amperometric Sensing

Amperometry quantifies the transfer of electrons during reactions at electrodes. Generally, when the reactants undergo oxidation or reduction reactions, there are electron gains and losses. After applying an appropriate operating potential, electron transfer occurs between the sensing electrode and the reaction environment, resulting in a recordable current. The intensity of the current reflects the concentration of the target analyte. Amperometric sensors combined with enzymes are commonly used for detecting small organic molecules [72], such as lactate [18], glucose [73] and ethanol [22]. During sensor operation, amperometric sensors often use the three-electrode system. This is necessary because after electrons are transferred from the solution to the electrode, the counter electrode supplies electrons to the solution, forming a current loop with the working electrode.

Enzyme activity is influenced by the external environment (temperature, pH, etc.) [74] and, therefore, affects the performance of the sensor. The sweat environment varies from individual to individual [74,75] so the results of the sensor must be calibrated. Previous studies have solved the correction of the sensor for temperature and pH changes [9,74,75]. Recently, Assaduzzaman et al. [9] performed pH and T corrections for the sensor using chronoamperometry to detect sweat glucose and lactose, used the chronoamperometric response of the sensor in artificial sweat to obtain the corresponding T and pH effects, and recalculated the target concentration according to the slope and intercept of the calibration curve in the reference state.

Amperometry has a faster response time, wider detection range, and higher sensitivity than potentiometry. However, amperometry is more susceptible to interference and its detection is often less stable than potentiometry. In addition, amperometry relies on the application of a potential or current, which is not required for potentiometry.

4.1.3. Voltammetric Sensing

In voltammetry, a continuously varying potential is applied to the working electrode and the response current signal is detected to record the current–potential curve and then analyze the composition of a solution. Depending on the potential scanning mode, voltammetry can be divided into cyclic voltammetry, differential pulse voltammetry, and square-wave pulse voltammetry. Voltammetry also involves electron transfer during detection, making three-electrode systems prevalent. It is worth noting that voltammetry may not be as selective as potentiometry and amperometry because different electroactive molecules may have similar reaction potentials [63].

Cyclic voltammetry (CV) can monitor electron transfer behavior, which can be used for electrochemical deposition to prepare electrodes [39] and characterize intrinsic electrochemical properties [76] to obtain the optimum electrode working potential. Magesh et al. [44] verified the selectivity and sensitivity of the sensing electrode to the target (nicotine) in buffer solution using CV. Square-Wave Voltammetry (SWV) is one of the fastest and most sensitive voltammetric techniques for sweat detection [77], because the square-wave voltage eliminates charging current and provides a higher detection threshold for substances such as caffeine [29] or heavy metal ions [78]. When the square wave in SWV is replaced by a pulse, it becomes differential pulse voltammetry. DPV is also suitable for detecting substances at low concentrations and can also characterize redox reactions, such as the binding of MIP templates to target molecules [43].

4.1.4. Impedance/Electrochemical Impedance Spectroscopy

Polymer composites impart moisture absorption to the sensor and the adsorbed moisture can change the dielectric and electrical properties of the electrode. Based on this principle, sweat composition can be monitored via the impedance principle, and the impedance change caused by sweat adsorption reflects the change in sweat composition or

volume [79]. Changes in fluid impedance can serve as an indicator of infection detection to aid wound healing [80,81].

Electrochemical impedance spectroscopy (EIS) is an alternating current-based electrochemical measurement technique. Compared to cyclic voltammetry, which scans the entire potential range at a given rate, EIS has the advantage of measuring at different set potentials [82]. However, it requires more complex data-processing methods than amperometry and potentiometry. The input–response relationship reflects the complex impedance characteristics of the sensing electrode, and the impedance modulus at a given frequency contains resistance and capacitance information, revealing the specific binding process of the receptor to the electrode [83–87]. Ganguly et al. [65] calibrated the sweat cortisol sensor using EIS to obtain a response curve that reliably reflects the concentration of synthetic sweat cortisol. Veeralingam et al. [88] utilized interdigitated electrodes to provide an external AC field to measure skin impedance at a frequency of 10 kHz to indicate skin hydration. The data obtained from EIS can be optimized into reliable output data using machine learning.

4.1.5. Others

Yin. L et al. [89] developed a stretchable epidermal sensor platform. An integrated electrochromic display displays the sampled signal from the electrochemical sensor in real time. An enzyme-modified electrode can be used to detect sweat pH, electrolytes, lactic acid, etc. For visualization, the sampled signal is converted to digital by the MCU and connected to ten addressable ECD pixels containing the PSS electrolyte. Compared to conventional electrochemical sensors with complex electronic systems, the patch has a lower energy consumption, is lighter and conforms to the skin. Compared to colorimetric sensors, there is no need to use a smartphone or camera to convert the results [89–94] and the detection results are more intuitive.

4.2. Optical Sensing Strategies

In 2014, Lee et al. [53] combined fluorescence and colorimetry to fabricate a sweat pore distribution sensor using the conjugated polymer poly(PCDA-Cs), pioneering the field of optical methods for sweat detection. The advantage of the optical method is that the detection results can be displayed in a relatively intuitive way. In recent years, more research has chosen to incorporate cameras and smartphones to record test results and perform image processing to achieve higher sensitivity. The use of smartphones avoids the use of laboratory instruments for analysis, and results can be analyzed without the need for a specialist. In addition, optical methods can partially overcome the shortcomings of enzymatic electrochemical sensors (enzyme consumption, temperature instability). The disadvantages of optical methods are limited resolution, sensitivity and detection limits, and it is difficult to distinguish small changes under naked-eye conditions. However, it is more suitable for the concept of dichotomy or semi-quantitative detection [95].

4.2.1. Colorimetric Sensing

In wearable sweat colorimetric sensors, the presence of the target analyte in sweat causes a visible color change in the reagent. Typically, there are two common ways of colorimetric sensing: one is to fix the colorimetric reagent in the designated chamber, a colorimetric reaction will occur after sweat flows in, and the colorimetric reaction will be analyzed according to the color changes; the second is to keep the colorimetric reagent in a fixed position, and the reagent will be taken away to produce a color block of a certain length after sweat flows in, and the composition will be analyzed according to the length. Most existing colorimetric sensors incorporate microfluidic systems to allow in situ sweat detection [91,96,97]. Methyl orange and bromocresol green can be used for the fluorescent detection of pH and enzymes for the detection of metabolites such as lactate. Promphet et al. [98] have shown that colorimetric detection can be achieved by co-depositing these reagents or substrates with chitosan and sodium carboxymethylcellulose on substrates.

Colorimetry has long been favored for its simplicity and low cost. From the beginning to the present, patch has been the mainstream form of the colorimetric sensor. For example, Yue et al. [99] presented a representative patch sensor that can use colorimetry to display a variety of physiological data (lactic acid, uric acid, pH, glucose and sweat rate) at the same time (Figure 2a).

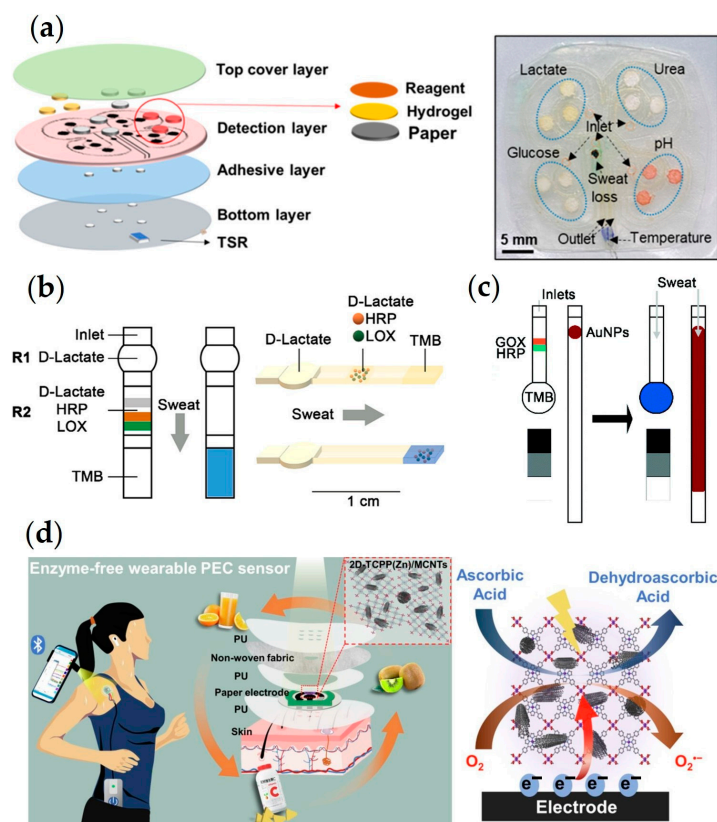


Figure 2. Sweat sensing devices using different strategies. (a) A colorimetric sensor that can display multiple physical and chemical data simultaneously. Reprinted from ref. [99], Copyright (2022), with permission from American Chemical Society. (b) A sweat sensing patch for fingerprint liveness-detection measurement. Reprinted from ref. [100], Copyright (2021), with permission from American Chemical Society. (c) A filter paper-based glucose colorimetric sensor. Reproduced from ref. [101], Copyright (2021) with permission from the Royal Society of Chemistry. (d) A two-dimensional material-based photoelectrochemical sensor for Vitamin C detection. Reprinted from ref. [102], Copyright (2023) with permission from Elsevier.

However, colorimetric sensors have the disadvantage of low sensitivity and a high lower limit of detection. Vaquer et al. [100] reported an enzyme-based lactate colorimetric sensor with an adjustable dynamic range (Figure 2b). The sensor also detects sweat volume at the same rate. The dynamic range of the sensor is modified by adding a competitive inhibitor (D-lactate) to different reservoirs. Sweat volume sensors measure the volume that is colored by gold nanoparticles (AuNPs) as they flow with sweat.

Using a similar structure, another study by the same group proposed a filter paper-based colorimetric blood glucose sensor. This sensor, with a lower detection limit, was used to prevent hypoglycemia during exercise [101]. Sweat brings glucose oxidase GOx and horseradish peroxidase HRP into the monitoring area to produce colorimetric reactions, and reagent partitioning can avoid spontaneous reactions between reagents (Figure 2c). By increasing the pore size of the filter paper, sensitivity and signal can be boosted. In addition, using a round tip to enlarge the sample capacity can also improve the signal.

4.2.2. Fluorescence Sensing

Fluorescence methods require an excitation light source and anti-optical interference equipment. The mechanism of this method is more complex than the color method, but the sensitivity and selectivity are better. A recent example is the fluorescence sensor proposed by Xu et al. [103] for the detection of Cl in sweat. Under UV irradiation, fluorescence signals can be recorded and warnings given during exercise.

Luminescent materials can also be used for fluorescence detection. Carbon quantum dots (CQDs) emit different colors of light under ultraviolet light irradiation and have pH-responsive properties after treatment. When the pH changes, the functional groups of the CQDs are ionized and affect the degree of deprotonation, causing the fluorescence color and intensity to change with different pH stimuli. Doping CQDs can be made into pH-sensitive sensing materials. Wei et al. [104] obtained a good pH response (4~7) by using N-doped CQDs (yellow fluorescence) and hydrogel impregnation doping, and a proof of concept was performed for sweat detection during exercise. In addition, biomass-derived CQDs can be extracted from natural wood fibers, which reduces environmental pollution during production and still achieves excellent fluorescence performance [105].

4.2.3. Others

Image acquisition and analysis using smartphones in optical methods is a common means, and smartphones play the role of receiver in this process. Furthermore, smartphones also have an excitation function that can send data, and act as a light source, sound source, etc. The photoelectrochemical (PEC) method combines the advantages of electrochemical methods (simple structure, fast response) and optical methods (low noise, high sensitivity). Yan et al. [102] proposed a photoelectrochemical sensor based on two-dimensional zinc porphyrinic MOF nanosheets/multi-walled carbon nanotubes (2D-TCPP(Zn)/MCNTs). The material (2D-TCPP(Zn)/MCNTs) used in the device stably generates hole-electron pairs under photo-stimulation, promoting vitamin C oxidation through their photoelectric conversion capability (Figure 2d). Driven by smartphone light, the 2D-TCPP(Zn)/MCNTs electrodes exhibit an enhanced cathode photocurrent response to vitamin C and can send sensing data back to the phone. In addition, polymer-based laser-induced graphene and In-doped CdS composites, capable of photocurrent sensing, can be used for Cu²⁺ detection [106]. Photoelectrochemical methods can also be employed for the label-free detection of lactate molecules [107].

There are many other optical principles that are applicable for sweat monitoring. Nan et al. [108] fabricated a sweat cortisol sensor using the localized surface plasmon resonance (LSPR) properties of gold nanoparticles (AuNPs) to detect the cortisol concentration from changes in extinction peaks in LSPR spectra.

For non-biochemical indicators such as sweat rate, colorimetric sensing is most commonly used. In addition, measurements can be made using flow sensors. Some flowmeters operate indirectly using thermal principles (thermal actuator and thermal sensor [46]). The work of Jose et al. [79] combined the impedance principle (fluid electrical properties) and the transient planar source (TPS, liquid heat flow rate) principle to design two coupled sensors to jointly measure sweat composition and fluid volume. The same idea is reflected in the work of Mei et al. [109]. This work integrates both electrochemical and colorimetric sensors, combining the advantages of both.

Innovative sensing strategies are expected to make a significant impact in real-world applications, provided that more research is conducted to test their stability and reliability. In addition, when selecting a sensing strategy for the device, it is necessary to consider not only the continuous detection time, sensitivity, detection limit, and other parameters of the strategy, but also the effect of the sensing environment and excitation conditions on the results. For example, optical sensors in low-light conditions require special image-processing algorithms, and underwater environments require a better sealing of the sensor. Table 2 summarizes the main features, advantages, and disadvantages of the above mainstream sensing strategies.

Table 2. A comparison of different sensing strategies.

Strategy	Overview	Advantages	Disadvantages	Refs
Potentiometry	Potential change is induced and converted into a voltage signal by the transducer	<ul style="list-style-type: none"> • Simplicity • Stability 	<ul style="list-style-type: none"> • Only suitable for detecting electrically charged substances • Accuracy difficult to guarantee at low concentrations 	[1,110]
Amperometry	Amperometry quantifies the transfer of electrons during reactions at electrodes	<ul style="list-style-type: none"> • Fast response time • Wider detection limits • Higher sensitivity 	<ul style="list-style-type: none"> • Sensing performance is affected by enzyme activity • Applied voltage required 	[72,74]
Voltammetry	A continuously varying potential is applied to the working electrode and the response current signal is detected to record the current–potential curve and then analyze the composition of a solution	<ul style="list-style-type: none"> • Multiple analytes can be analyzed simultaneously using voltage scans on the same two electrodes • Higher detection limit than chronocurrent method 	<ul style="list-style-type: none"> • Different electroactive molecules may have similar reaction potentials, so voltammetry may not be as selective as voltage and amperometric methods 	[63,111]
Electrochemical impedance spectroscopy	The impedance varies with sweat composition, and the impedance modulus at a given frequency contains resistance and capacitance information, revealing the specific binding process of the receptor to the electrode	<ul style="list-style-type: none"> • Ability to measure at different selected potentials compared to cyclic voltammetry • No need to couple electrochemical inactives to redox labels 	<ul style="list-style-type: none"> • Requiring complex subsequent data processing and high time costs 	[112–114]
Colorimetry	The colorimetric reaction of sweat with the reagent reflects the concentration of the target analytes	<ul style="list-style-type: none"> • Simple operation • Low cost 	<ul style="list-style-type: none"> • Lower resolution makes it difficult to quantify the indicator • Relatively high detection limit 	[96,100,101]
Fluorescence sensing	Under light excitation, the fluorescence signal changes depending on the target analyte	<ul style="list-style-type: none"> • Better sensitivity and selectivity than colorimetric methods 	<ul style="list-style-type: none"> • Requiring excitation light source and anti-light interference equipment, the mechanism is more complex 	[103,104]

5. Materials, Structure and System Composition of Sweat Sensor

5.1. Sensing Materials

5.1.1. Common Materials for Electrodes

Common counter-electrode materials include gold, platinum and carbon. The reference electrode is typically Ag/AgCl. The working electrode is divided into enzymatic reaction electrode, molecular selection electrode [115] and ion-selective electrode. When the sensitive membrane of the ion selective electrode contacts the solution, an electrical potential is generated at the interface that is directly related to the corresponding ion concentration. For example, the multiplexed sensor proposed by Mei et al. integrates five electrochemical sensors detecting lactate, glucose, pH, Cl^- and urea, of which the detection of lactate and glucose uses enzyme-modified electrodes, using current changes to detect

concentration; pH, Cl^- and urea are sensed by electrodes modified with PANI, Ag treated with FeCl_3 and NH_4^+ ion-selective membranes, respectively. As mentioned above, sensing materials are also gradually developing in the direction of multifunctional multi-modulus in the form of arrays. For example, the multiplexed sensor proposed by Mei et al. [109] integrates five electrochemical sensors, lactate, glucose, pH, Cl^- and urea, of which the detection of lactate and glucose uses enzyme-modified electrodes that rely on current changes to detect concentration; pH, Cl^- and urea are sensed by electrodes modified with PANI, Ag treated with FeCl_3 and NH_4^+ ion-selective membranes, respectively (Figure 3a). As mentioned above, sensing materials are helping to improve devices in a multifunctional and multimodal way in the form of arrays.

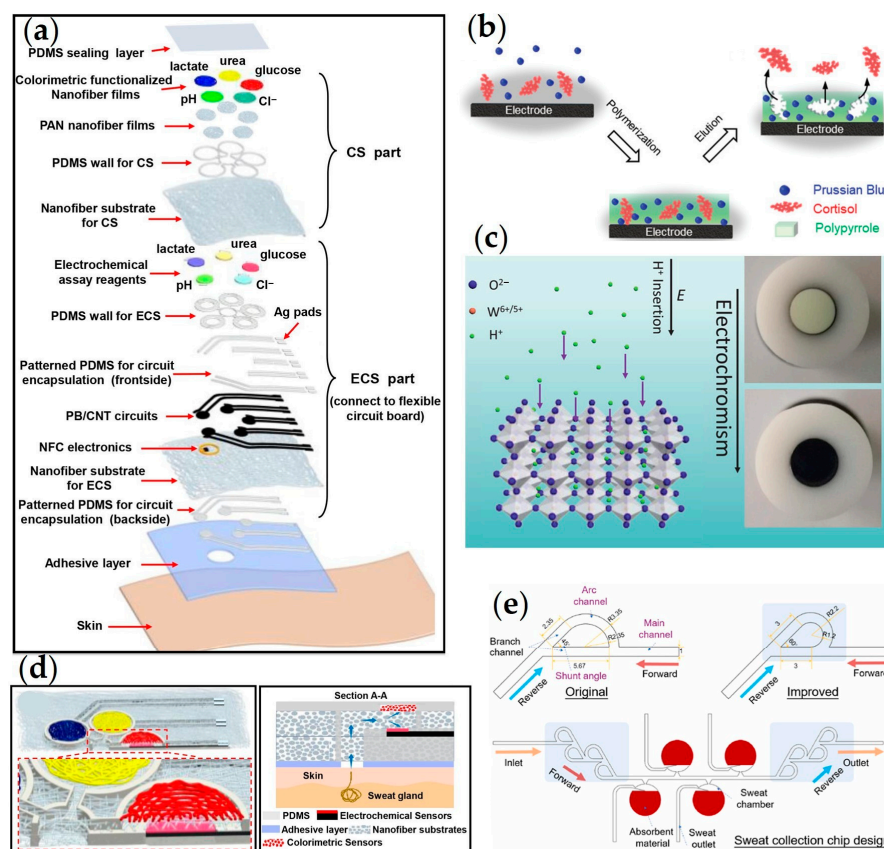


Figure 3. The role of newly developed materials in sweat sensors, and the demonstration of novel microfluidic channels. (a) An electrochemical sensor and electrode modification method for the simultaneous detection of lactate, glucose, pH, Cl^- and urea. Reprinted from ref. [109], Copyright (2023) with permission from Elsevier. (b) A molecularly imprinted polymer combined with a redox probe touch-based cortisol sensor. Reprinted from ref. [116], Copyright (2021) with permission from John Wiley and Sons. (c) A pH sensor based on the inorganic material WO_3 . Reprinted from ref. [117], Copyright (2021) with permission from John Wiley and Sons. (d) A nanofiber-based microfluidic analysis system that collects and transports sweat using a highly porosity, hydrophilic nanofiber membrane. Reprinted from ref. [109], Copyright (2023) with permission from Elsevier. (e) An improved design of the Tesla valve. Reprinted from ref. [118], Copyright (2022) with permission from Elsevier.

Recent studies have focused on the repeatability of electrode materials in wearable sensor electrodes [109,119]. The application of reusable electrodes reduces the need for replacement, thereby improving the user experience.

5.1.2. Nanomaterials

As materials science continues to advance, the application of nanomaterials has become increasingly sophisticated. Due to their unique properties, such as porosity, rigidity, and impedance, as well as their customizable electrical and wetting properties, nanomaterials have been widely used in the fabrication of sensing materials, substrates, and other components to enhance sensor performance. Lin et al. [120] utilized N-GODs to anchor a PANI matrix as a sensing electrode, resulting in improved sensitivity and stability while avoiding the cracking commonly associated with rigid electrodes. Furthermore, the modification of electrodes with metal nanomaterials can optimize sensing performance. For example, the modification of a Prussian blue electrode with gold nanoparticles (AuNPs) yielded a larger amperometric response [121]. In the fabrication of electrochemical electrodes, metal nanomaterials are often combined with redox graphene (rGO) [122,123], which serves as a supporting substrate to enhance sensitivity. Due to its high electron mobility and large active surface area, this composite often leads to significant improvements in the sensitivity and accuracy of sensors. Additionally, such nanocomposites generally exhibit excellent electrocatalytic activity [124,125]. Yu et al. [126] developed a Cu_xO -nanoflake (NFs)/Cu nanoparticles (NPs) nanocomposite as a sensing material. The sensor was enriched with more active sites, a low detection limit, high selectivity, and resistance to bending and twisting. Assaduzzaman et al. [9] developed a flexible, multifunctional patch based on laser-induced graphene (LIG) combined with hybrid nano-porous carbon (H-NPC). Sensors based on nanomaterials exhibit excellent electrochemical activity, reliability and a wide detection range.

5.1.3. Two-Dimensional Materials

Graphene: As a monolayer two-dimensional material, Graphene has long been of interest to researchers. Special variants of graphene, such as graphene oxide and reduced graphene oxide, are widely used in wearable sweat sensors. Their high surface-area-to-volume ratio provides a large number of reaction sites, excellent electrocatalytic performance and high electron mobility. Graphene is often used as a substrate for electrodes and is combined with other materials or modification methods to enhance the overall performance of the electrode. After modification with graphene, the sensing electrode shows high sensitivity, good selectivity and flexibility, enabling the detection of small-molecule concentrations such as glucose [127,128], lactate [9], cortisol [26] and uric acid [129]. Wang, Y et al. [130] synthesized reduced graphene oxide (RGO) in situ on cotton fabric (CF). This imparted softer physical properties to the graphene material while achieving a fast response and excellent selectivity. In addition, the electrodes can be fabricated by engraving graphene films into specific patterns using laser-engraving techniques. Wang, M et al. [43] fabricated an electrode based on laser-engraved graphene (LEG) and Molecularly Imprinted Polymers (MIP) that can be repeatedly regenerated in situ. This electrode can be used to assess amino acid intake levels [131]. LEG can likewise be modified with nanomaterials (e.g., AuNPs) for highly sensitive electrochemical detection. According to the research conducted by Tu et al. [132], the deposition of AuNPs via pulsed potential results in their uniform distribution throughout the mesoporous graphene structure. This enhances their catalytic ability and provides a large number of specific binding sites. Laser-induced graphene (LIG), on the other hand, produces graphene directly on polymers using lasers without needing a film [133]. Feng et al. [134] demonstrated the use of LIG and single-walled carbon nanotubes (SWCNT) in the development of a sweat sensor. The LIG fabrication process is both rapid, taking less than a minute, and inexpensive. Additionally, laser-scribed graphene (LSG) has also been shown to have potential for use in chemical sensing [135]. The emergence of LEG and LIG has made the large-scale fabrication of graphene devices increasingly promising.

MXene: MXene is a novel material discovered by Gogosti in 2011 [136]. It is a two-dimensional transition metal carbide and nitride with a tunable structure and can exhibit excellent electrical, optical, catalytic and mechanical properties when appropriately modi-

fied [137]. The formation of composites with MXene and other materials, such as Pt and polymers, can result in enhanced performance, making it suitable for use in wearable devices. $\text{Ti}_3\text{C}_2\text{T}_x$ was the first synthesized MXene material due to its low formation energy and in wearable sweat-sensor studies; $\text{Ti}_3\text{C}_2\text{T}_x$ is a commonly used MXene material [138]. $\text{Ti}_3\text{C}_2\text{T}_x$ exhibits high electrical conductivity, excellent hydrophilicity, and a large number of active sites and terminal functional groups. These properties reduce signal interference and promote the adsorption of gas and water molecules, making $\text{Ti}_3\text{C}_2\text{T}_x$ well-suited for use in the manufacture of sensors [139]. Sharifuzzaman et al. [140] reported a catalyst composed of MXene/fluoropolymer-derived porous TiO_2 nanomaterials. On the other hand, Magesh et al. [45] developed a carbon (Pearlman catalyst) using a MXene/palladium hydroxide-loaded composite (MXene/ $\text{Pd}(\text{OH})_2/\text{C}$) for electrochemical sensors, achieving good selectivity, sensitivity and stability. Li et al. [141] used MXene to develop a fully optimized glucose sensor. Pt/MXene nanomaterials were fabricated using Pt nanoparticles for glucose detection on MXene nanosheets, yielding a wide linear range under neutral conditions. The sensor substrate was a conductive hydrogel synthesized from MXene and polyvinyl alcohol (PVA), providing reliable stability to the sensor.

5.1.4. Hydrogel

Hydrogel-based flexible sensors possess numerous properties such as compatibility, self-healing, and adhesion [142]. Due to their water content of up to 90%, they exhibit excellent biocompatibility, electrical conductivity, and flexibility. The use of hydrogel as a sensor substrate or electrode material can improve the sensing performance. The elastic hydrogel system results in a skin-like base that can significantly improve the wearability and mechanical deformability of the device. It has been used in applications such as tissue engineering [143,144], drug delivery carriers [145], soft robots [146,147], and wound dressings [148,149]. Wang et al. [150] used TPU film to combine hydrogel and conductive material to provide the sensor with excellent mechanical and electrical properties at the same time, verifying the ability of hydrogel to improve comfort.

Gao et al. [151] used porous hydrogel instead of liquid electrolyte on sensor electrodes, maintaining better conductivity while achieving improved swelling and biocompatibility. A recent study showed that glycerin gel can also achieve alternative functions while providing anti-bending and sweat absorbing effects [127]. As a new type of gel, noble metal aëro-/hydrogels possess the properties of both aërogl materials and noble metal nanoparticles [152,153]. Their highly branched, fused nanowire structure imparts inherent self-healing and flexible properties, making them promising for flexible sensing [154,155]. Li et al. [156] designed a bis-structured Pt-Ni hydrogel that achieved the aforementioned excellent properties and remained stable for two months. Chen et al. [129] reported a wearable biosensing platform based on metal aërogl using three-dimensional porous bis-structured aërogl (N-rGO/Au DAs) consisting of gold nanowires and N-doped graphene nanosheets as working electrodes. The high surface area and porous structure, as well as the synergistic effect of Au and N-rGO aërogl, enable better catalytic and electron-transfer properties than mono aërogl, facilitating non-enzymatic uric acid sensors.

5.1.5. Organic Electrochemical Transistors

An organic electrochemical transistor (OECT) is a low-cost, highly sensitive device that responds to physical stimuli, chemical functionalization, and shape changes. The OECT is composed of an ion-permeable organic semiconductor channel (OSC) connecting the source and drain electrodes. Its operation involves the conversion of the ionic current between the electrodes into a modulation of the polymer film conductivity, allowing for the detection of electrolyte solution concentrations. Poly(3,4-ethylenedioxythiophene):poly(styrenesulfonate) (PEDOT:PSS) is commonly used as a conductive pathway between the source and drain of the OECT due to its ability to amplify signals, ease of miniaturization, and excellent biocompatibility [157,158]. PEDOT:PSS-based OECTs exhibit high transconductance ($\approx 2 \text{ mS}$) at low voltages ($< 0.5 \text{ V}$) [159], making them promising for use in biosensing applications.

However, these OECTs are sensitive to ionic strength [160] and the PEDOT:PSS channel accepts all cation insertions from the analyte, resulting in a lack of selectivity [161]. The selectivity of OECTs for analytes in sweat can be improved through the use of an ion-selective membrane (ISM), which permits only specific ions to pass through. In 2014, Sessolo et al. [162] first proposed the incorporation of an ISM into an OECT for the detection of K^+ , inspiring subsequent research in the field of wearable sweat sensors. Coppedè et al. [163] later proposed an OECT using an ISM for the detection of Ca^{2+} , with the device being fabricated by functionalizing textile fibers. It is worth noting that many recent studies on OECT sweat sensors have incorporated textiles as a platform. Textiles are easy to prepare and can be integrated into clothing, and the detection of target analytes is not limited to ions. Tao et al. [164] developed a fabric-based OECT lactate sensor that enables PEDOT:PSS to exhibit high transconductance in both depletion and accumulation modes. Fang et al. [165] addressed the issue of insufficient transconductance in fiber OECTs by modifying carbon nanotube (CNT) fiber grids. Qing et al. [166] further integrated fiber OECTs with thermoelectric fabrics, using a manufacturing substrate composed of cotton/poly(3,4-ethylenedioxythiophene):poly(styrenesulfonate)/dimethylsulfoxide/(3-glycidyloxypropyl)trimethoxysilane (PDG) yarn, which is lightweight, strong, and sweat-resistant.

5.1.6. Other Materials

There are numerous reports on fiber-based wearable electronics, with many studies focusing on the application of fibers for physical sensing, such as pressure [167] and thermal [168] sensing. Instead, Wu et al. [169] focused on biochemical parameters to develop a flexible microelectronic fiber that can be woven into textile substrates. Detection of UA oxidation or Na^+ concentration can be achieved by modifying ion-sensitive membranes or nanoparticles.

Garcia-Rey et al. [5] conducted a proof-of-concept study on alginate-based biological systems to evaluate the efficacy of the colorimetric determination of sweat glucose. Alginate beads were obtained by integrating enzyme assays, consisting of GOx, HRP, and TMB, into the alginate scaffold. The porosity of the beads enabled highly sensitive glucose detection, and a similar system has been used in previous studies to calibrate and detect lactate in sweat [170]. Furthermore, another report stated that the integration of TiO_2 nanotubes into alginate can provide enhanced hydrophilicity, further improving the sensing performance of this material [171]. The touch-based cortisol sensor reported by Tang et al. [116] embeds Prussian blue redox probes within a molecularly imprinted polymer (imprinted polypyrrole, PPy, film) network (Figure 3b). The selective binding of cortisol to the imprinted PPy film impedes PB charge transfer, resulting in a rapid change in current.

Tang et al. [117] reported a WO_3 -based pH sensor. According to the article, conventional pH sensing methods primarily utilize organic materials, which carry the risk of biological toxicity (Figure 3c). As an alternative, WO_3 is an inorganic and non-toxic material that is sensitive to hydrogen ions. However, its exchange rate is very low. The embedding of lattice H^+ transforms WO_3 from a monoclinic phase to a cubic phase (H_xWO_3), enhancing its H^+ exchange capacity and reducing its resistance, thereby improving detection sensitivity and response speed.

The use of composite sensing materials is becoming an increasingly popular trend in the research into wearable sweat sensors. While individual materials may have specific limitations, composite materials can be specifically designed to balance the strengths and weaknesses of different materials to achieve the desired functionality. Nanomaterials are also gradually becoming significant in this field. The various materials mentioned above can be nanosized or combined with nanomaterials to produce interfaces or electrodes with a large number of active sites, a large surface area, and good mechanical properties, thereby optimizing sensor performance.

5.2. Forms and Structure

5.2.1. Development of Sweat Sensor Forms

In the early years of wearable sensor research, various forms of sensors, including tattoos, wristbands, and patches, have been reported. In 2012, Professor Joseph Wang's research team reported a tattoo-based electrochemical sensor [172]. Based on this research, many applications, including the detection of ammonium [173], lactate [75], and sodium [110], have been developed in vitro and attached to the skin using transfer technology. Tattoo sensors integrated with carbon fiber exhibit excellent immunity to disturbances such as stretching, bending, and skin abrasion, and have better electrical performance than screen-printed electrodes. In addition, these sensors can be combined with artistic tattoos, which has attracted the attention of many researchers. In practice, tattoo-based sensors are more like a new type of electrode. While research on tattoo-based sensors has seen significant improvements, their popularity in subsequent research has gradually declined. Katseli et al. [7] proposed a 3D-printed electrochemical ring for sweat glucose detection. The complex fabrication process of wearable sensors is simplified by embedding conductive plastic electrodes in a ring holder and using a dual-extrusion 3D printer and commercially available filaments in a one-step printing process. In addition to the above research, many sweat sensors are now manufactured in patch form, including readable disposable sensor patches and system-based patches.

Currently, the research focus has gradually shifted, first from single-parameter to multi-parameter detection. The human body system is complex and constantly in a dynamically changing environment. As such, it is difficult to fully express the physiological health status of the human body by interpreting a single parameter. Consequently, more research is now focused on multi-parameter detection, including metabolites and electrolytes [174], sweat analytes and sweat rate [175], providing data on multiple biomarkers for analysis.

From single-component components to system-level studies, Gao et al. [6,176] proposed a sensor array capable of multiplexed sweat composition analysis, in 2016. The array was connected to integrated circuits and flexible circuit boards to simultaneously detect sweat metabolites, such as lactic acid and glucose, and electrolyte ions, including pH, calcium, sodium, and potassium. This study aimed to propose a design scheme for wearable sweat sensors from the perspectives of system integration, signal calibration, and multiplexing. This groundbreaking work provided researchers with a more complete system-level design.

Multi-function sweat sensors broaden the information collection range of single-channel sensors, and further expansion (e.g., combining physical signal detection such as acoustics) is expected to provide a more comprehensive picture of human health information. Sempionatto et al. [177] report a multiplexed sensor capable of not only detecting multiple biomarkers in sweat, but also integrating an ultrasound transducer to detect blood pressure and heart rate. One of the issues that must be considered when multiplexing integrated sensors is to prevent signal crosstalk from affecting the reliability of the data from each sensor. A solution to the signal crosstalk problem was proposed that spatially separates components at optimal distances and prevents crosstalk between acoustic and electrochemical transducers with solid-state ultrasound and sensing hydrogel layers.

While the concept of multiplexed detection and system design research is on the rise, making sensor systems lighter is also an important issue in the development of complex sensors. Gao et al. [178] proposed a lightweight flexible sensor based on their previous research. To achieve this, the researchers aimed to make materials that fit the body lighter, such as paper-based and textile sensors.

A disadvantage of using sweat as a detection target is the small sample size available at rest. To overcome this limitation, flexible sensors with integrated sweat-stimulation capabilities are being developed. Sam et al. [179] used iontophoresis electrodes to deliver agonists to stimulate sweat gland secretion, which has gradually become the main method for sweat induction. Research into natural sweat production is also increasing due to its non-invasive nature.

Research on sweat sensors does not stop at simply completing the detection function. Researchers also expect them to have therapeutic capabilities. Lee et al. [128] used microneedles to design sweat sensors capable of transcutaneous drug delivery, adding medical value to wearable devices.

As wearable sweat sensors move closer to practical applications, portability and miniaturization are inevitable trends for clinical and everyday consumer markets [180,181]. One important method for achieving device miniaturization is to replace traditional standard discrete components with integrated circuits. Wang et al. [182] reported an ultra-small wearable sweat sensing system with a size of only $1.5\text{ cm} \times 1.5\text{ cm}$. Its core processing chip, the MS02 chip, integrates functional circuits such as amplification and filtering, which greatly reduces the overall system area while maintaining sensor performance.

5.2.2. Structure of Sweat Sensor

Wearable sweat sensors can be roughly divided into two categories based on whether they have a sweat transport structure: patch and microfluidic-based devices. The former undergoes electron transfer or optical reactions directly upon contact with sweat, while the latter collects or transports sweat to electrodes or reagents through microfluidic channels for detection. Taking electrochemical detection as an example, when the detection target is relatively simple, sweat can be brought directly into contact with the electrode to achieve rapid real-time monitoring. However, when multiple analytes are involved, the lack of sweat sample becomes more noticeable, making it difficult to supply multiple electrodes for simultaneous analysis. Timed sampling with an absorbent patch or a regular sweat collector can solve this problem, but it increases the effort required [183]. In addition, changes in sweat rate over time and across body parts, combined with factors such as epidermal contaminants and sweat evaporation, can easily cause fluctuations in the results of sweat sensor patches [184]. By incorporating microfluidic channels, sweat can be collected and distributed to different sensing electrodes on demand, overcoming problems such as inadequate sweat sample volume, instability, and sweat evaporation. The effects of contamination can also be reduced with specially designed channels.

Microfluidics: Microfluidic systems have the advantages of simple structure, strong ductility, and storage and transport capabilities. By designing the size (e.g., capillary [115], width variation), structure (e.g., serpentine structure, fiber, reservoir distribution), and other properties of the microfluidic channels, they can acquire specific capabilities. Examples include designing numerous pathways for the multi-modal analysis of sweat [96] and building attractive fluid dynamics and reservoirs for rapid filling [185]. Microfluidics have long been used in wearable sweat sensors as channels for the rapid sampling, collection, and analysis of sweat. Microfluidic sensing patches can be mass-produced using techniques like Roll-to-Roll (R2R) printing [186], a low-cost rotary screen printing process. Biocompatible and stretchable materials including PDMS [90] (polydimethylsiloxane) and PET (polyethylene terephthalate) are commonly used to construct microfluidic channels, allowing sensors to be integrated anywhere on the body [187].

As mentioned above, the structure of microfluidic channels can be customized. However, a more complex microfluidic system does not necessarily result in better performance. For instance, the flowmeter-based sweat rate sensor reported by Kwon et al. [46] relies on a short, straight microchannel that is thermally coupled to sweat to accurately measure temperature differences and obtain flow values. Microfluidic channels can also be designed as three-dimensional structures, allowing the vertical integration of multiple modules for sampling, transport, sensing, and storage [188].

The microfluidic channel is a semi-open system that depends on capillary action to transport sweat during collection. As such, it is important to control the fluid flow within the channel. Shi et al. [118] proposed the addition of forward and reverse Tesla valves to the inlet and outlet to prevent inlet backflow, and reduce contact between the outlet and the environment (Figure 3e). This design is highly suitable for low-flow-rate conditions, such as sweat monitoring.

With the ongoing advancement of materials science, new microfluidic systems have been developed to address the limitations of traditional hollow microfluidic channels, such as contamination, miniaturization, and diffusion of chemical agents. Currently, there are studies exploring the combination of nanofibers with microfluidic channel materials. Mei et al. [109] reported a nanofiber-based microfluidic analysis system (NFMAS). This system utilizes highly porous and hydrophilic polyimide/sodium dodecyl sulfate (PI/SDS) nanofiber films as a microfluidic network substrate for collecting and conducting sweat (Figure 3d). The system features both electrochemical and colorimetric sensing modules, which are separated by nanofibers. These sensors exhibit excellent mechanical properties and resistance to contamination. In subsequent research, the same group continued to apply this nanofiber microfluidic technology to fabricate flexible sensors [189], with the goal of better improvement.

Another approach is to use paper-based microfluidics. By cutting paper into a channel shape, sweat can be transported by capillary action [190,191]. Also, paper can be folded to form three-dimensional structures, allowing the creation of more complex channels. Liang et al. [192] demonstrated a three-dimensional paper-based microfluidic electrochemical device (3D-PMED). The device is constructed by prefabricating a pattern on cellulose paper and folding it into a five-layer stacked structure containing a sweat collector, vertical channel, transverse channel, electrode layer, and sweat evaporator. Table 3 presents a comparison of currently commercially available microfluidic sweat wearable sensors with those from recent research.

Table 3. A comparison of microfluidic sweat sensors on the market and in the latest research.

Device	Localization	Indicators	Mechanism	Features	Ref
Nix Hydration Biosensor produced by Nix (Boston, MA, USA)	Biceps brachii	Sweat rate, electrolyte loss rate, and sweat composition	An electronic pod clips onto the single-use sweat patch and wirelessly transmits the test data to a cell phone, watch or bike computer.	<ul style="list-style-type: none"> Real-time tracking of fluid and electrolyte loss during workouts Calculate the Nix Index™ for a given workout in the future based on the weather forecast 36 h of battery life The patch weighs less than 0.5 ounces and is similar in size to a Garmin dial 	[193]
AbsolusSweat P1 produced by Shenzhen Refresh Biosensor Technology Co., Ltd. (Shenzhen, China)	Chest, forehead and upper arm	Glucose, potassium, sodium, sweat volume, sweat rate	The sweat analysis terminal is connected to the sensing patch, which analyzes the sweat and transmits the data to the app.	<ul style="list-style-type: none"> Pre-hydration plan based on historical data Advice on supplementation during exercise Personalized Recovery Plan After Exercise Timely alerts to prevent injuries 	[194]
Gx Sweat Patch produced by Gatorade, PepsiCo Inc. (New York, NY, USA)	Inner left forearm	Sweat rate, fluid loss, and sodium loss	Scanning patches, processing and analyzing images using Gx applications.	<ul style="list-style-type: none"> Gx app records sweat data as a sweat profile. No patch is required for workouts in conditions similar to the profile. Targeted advice on hydration and nutrition The patch measures 2.5 in. × 1.5 in. and weighs 1.25 oz. Valid for 20 to 120 min 	[195]

Table 3. Cont.

Device	Localization	Indicators	Mechanism	Features	Ref
An on-skin platform for wireless monitoring	Inner forearm	Sweat rate, sweat loss and temperature	The platform's electronic system contains a thermal actuator and thermistor, which utilizes the temperature difference to calculate the flow rate and, thus, the sweat rate.	<ul style="list-style-type: none"> • Short and straight microfluidic structure • Expansion modules (colorimetric patches) can be integrated into the platform to measure other biomarkers 	[46]
An epidermal wearable microfluidic patch	Inner forearm	Cl^- in sweat, Ca^{2+} in interstitial fluid (ISF)	The patch uses iontophoresis to extract sweat and ISF, detecting both ions simultaneously in a three-dimensional microfluidic channel.	<ul style="list-style-type: none"> • Three-dimensionally structured microfluidic channels for efficient sampling and storage of fluids 	[188]
Nanofiber-based microfluidic systems with integrated dual-mode sensing arrays	Wrist	Lactate, urea, glucose, pH, Cl^-	The system direct sweat to different microchannels and chambers for electrochemical and colorimetric detection, respectively.	<ul style="list-style-type: none"> • nanofiber-based microfluidic network (NFMN) • Dual-mode sensing arrays (electrochemical array and colorimetric array) 	[109]
An integrated three-dimensional paper-based microfluidic electrochemical device (3D-PMED)	Forearm	Potassium	Sweat is driven through the capillary tube into the vertical channel, where it flows and completes the detection.	<ul style="list-style-type: none"> • Five-layer three-dimensional structure composed of folded patterned cellulose paper • Flow driven by sweat evaporation 	[192]

5.3. System and Module

5.3.1. Sweat Collection

There are several common methods for collecting sweat using wearable sensing systems. One approach is to use external stimuli, such as iontophoresis, to induce the release of sweat from the skin. Another approach is to collect sweat produced naturally during high-intensity exercise or to absorb sweat from the skin under resting conditions [190].

Iontophoresis: Iontophoresis involves the use of a pair of positive and negative electrodes. The anode releases pilocarpine or other long-acting sweat-inducing drugs, such as carbachol [196], to induce sweating without significant stimulation. The anode used in iontophoresis is often positioned in the center of the measuring electrodes [197] to enable real-time sweat sampling or detection. However, due to the mixing of sweat and gel and the lack of dynamic sweat sampling, this method can result in a limited number of effective samples and reduced measurement accuracy [43]. By combining iontophoresis with microfluidics [188], induced sweat can be collected and directly transferred to the sensing electrode, resulting in a more stable and quantifiable sample. Bolat et al. [196] reported on a specialized wearable, single-step sensing platform that integrates iontophoresis with microfluidics. The iontophoresis electrode is positioned directly around the PDMS microchannel, stimulating sweat glands near the microfluidic inlet. This allows secreted sweat to precisely enter the channel and be delivered to the sensor. A similar approach has been used by Wang et al. [43] in their sweat sensing patches.

Hydrophilic/Hydrophobic Substrate: Zhang et al. [97] developed a stretchable, colorimetric sweat sensor that utilizes the large wettability gradient between a superhydrophobic substrate and superhydrophilic assays to collect sweat (Figure 4a). Superhydrophilic assays are composed of elastomeric nanofiber textiles modified with SiO_2 nanoparticles, rather than the more commonly used filter papers. Superhydrophobic substrates are created by

modifying the surface of elastomer substrates with nanoparticles. This elastic substrate, featuring a wetting gradient and favorable comfortability, is well-suited for non-invasive and efficient sweat collection.

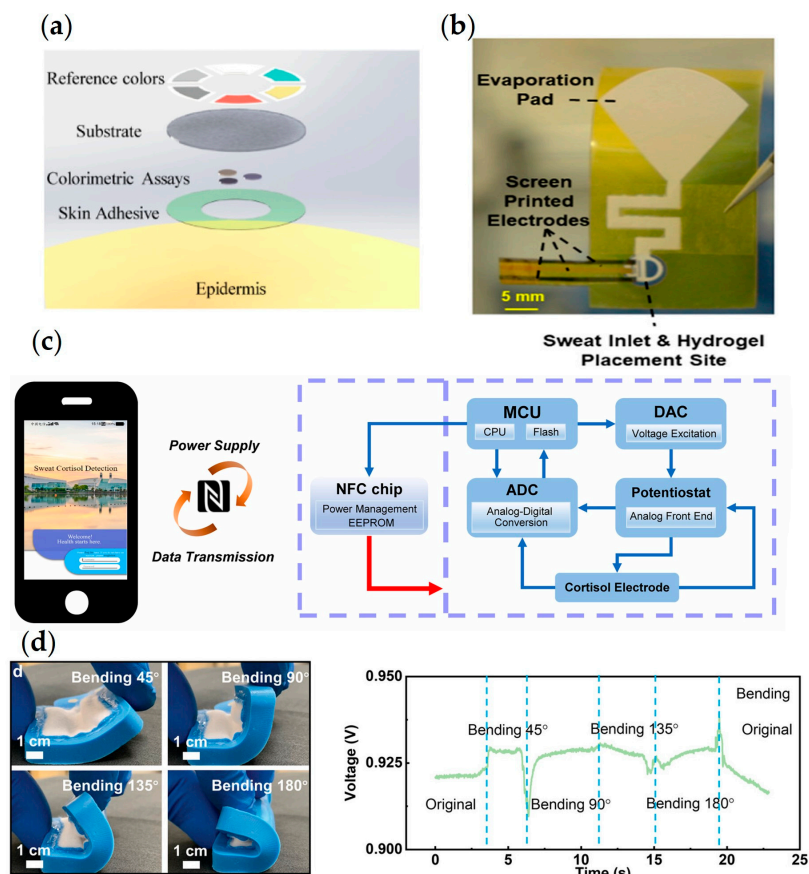


Figure 4. Development of different system modules for wearable sweat sensors. (a) A sweat sensor using a superhydrophobic substrate and superhydrophilic assays capable of collecting sweat using an ultra-large wettability gradient. Reprinted from ref. [97], Copyright (2021), with permission from American Chemical Society. (b) A sweat sensor based on a specially designed paper channel. The evaporation pad after bending and increasing the area can delay channel saturation and increase the rate of sweat evaporation. Reprinted from ref. [190], Copyright (2021), with permission from American Chemical Society. (c) A sweat sensor that uses NFC for wireless communication and function. To start the measurement, the mobile phone should be held close to the sensor. Reprinted from ref. [198], Copyright (2021), with permission from Elsevier. (d) A flexible sweat-activated battery that uses soft silicone as a package. Reprinted from ref. [199], Copyright (2021), with permission from John Wiley and Sons.

Hydrogel for Natural Sweat Extraction: Skin-conforming hydrogels have a hydrophilic interface. The hydrogel that adheres directly to the skin has the ability to reduce Laplace pressure, which prevents sweat from forming on the skin surface. In addition, water-based patches are an effective matrix for metabolite extraction, and the proper thickness of hydrogel patches can substantially improve the sensor's capability to collect biomarkers [76]. Lin et al. [76] developed a wearable hydrogel patch that leverages the above advantages to quickly collect natural sweat from the hands. Tang et al. [116] designed a sensor that can rapidly detect cortisol through fingertip contact, using a highly permeable, porous PVA hydrogel. Its detection results can be obtained within 3.5 min of fingertip contact. Patches utilizing PVA hydrogel also exhibit excellent resistance to staining [106].

Sweat Transport and Management: When continuously monitoring sweat, it is important to consider how to prevent the accumulation of old sweat, as residual sweat can

saturate the device and affect its long-term performance. Saha et al. [190] introduced an osmotic wearable for lactate sensing in sweat (OWLSS) that is capable of continuous monitoring, utilizing a specially designed paper channel to effectively manage sweat (Figure 4b). Adding an evaporation pad to the channel and creating a serpentine channel path to increase the distance sweat must travel before reaching the evaporation pad can help delay channel saturation. Increasing the area of the evaporation pad also ensures that sweat evaporates faster than it flows into the channel under all conditions, allowing for continuous monitoring.

5.3.2. Signal Transmission and Power Management

Wearable sweat sensors require real-time monitoring over extended periods of time, necessitating the use of wireless signal transmission. Technologies such as Bluetooth, NFC, and RFID are commonly employed in the electronic systems of wearable sweat sensors due to their advantages of miniaturization and low power consumption. The communication and control of wearable sensors consume energy, particularly in the signal processing and wireless transmission circuits, such as those utilizing Bluetooth or radio frequency transmission [200–202]. However, the traditional battery power supply method hinders the continuous operation of the sensor on the skin due to its difficulty in deformation, poor battery life, and the presence of harmful substances. To address the issue of energy consumption, new battery materials suitable for use in wearable devices have been developed. In their study, Liu et al. [203] mentioned the use of super-resilient hard carbon nanofabrics (s-HCNFs) as carbonaceous anode materials. This high-capacity material exhibits excellent mechanical stability under twisting and folding, and its properties can be further enhanced by designing it as a 3D micro- or nanolayered structure. These properties make s-HCNFs well-suited for use in the fabrication of flexible wearable devices. Moreover, researchers are also applying scientific research results such as self-generation, wireless power supply, and flexible batteries to integrate them into wearable sensors.

NFC: The advantages of NFC include low power consumption, few components, and small size. Only small coils and NFC chips are required to achieve wireless signal transmission [204]. NFC chips and sensors can be magnetically coupled to form a stable system [90]. The modulated antenna can also provide wireless energy supply [35]. Cheng et al. [198] developed a sweat cortisol sensor that uses NFC for wireless communication and power (Figure 4c). When detection is required, the NFC antenna is powered after the smartphone approaches the patch to power the circuit and begin measurement. The performance of the NFC antenna is also verified under different radii of curvature to ensure that the NFC chip can still provide stable power when the patch is bent.

Biofuels and Sweat-Activated Batteries: Sweat has the potential to provide electricity support for epidermal electronics as a sustainable bioenergy source [205,206]. Biofuel cells provide power based on the bioenergy in sweat. Yu et al. [200] report on a lactate biofuel cell based on full perspiration-powered electronic skin (PPES). The enzyme-catalyzed batteries exhibit a higher current density and stability. The electrolytes in sweat (Na^+ , K^+ , Cl^-) can also be used for electrochemical energy storage. Chen et al. [207] designed an array of sector electrodes (using copper and zinc thin films) to create a sweat-based energy generator based on redox reactions. Manjakkal et al. [208] report a supercapacitor using PEDOT: PSS as the active electrode and current collector. This material has been used in sensitive electrodes of electrochemical sensors [6] due to its high conductivity, large voltage window, and good mechanical properties.

In response to the need for flexibility, Liu et al. [199] developed a flexible sweat-activated battery that can be directly integrated onto the skin (Figure 4d). Soft silicone is used for fixing and loading functional materials as a package housing. Two Nylon fabric bags containing electrolyte are used to stabilize the output voltage under various deformation conditions.

Triboelectric Nanogenerator: Since the invention of triboelectric nanogenerators (TENGs), many sensor platforms incorporating TENGs have been reported [209–211]

due to their advantages of a high output voltage, power, low cost, and ease of fabrication [212–215]. In sweat-sensing applications, methods for optimizing TENGs are also being explored. Zahed et al. [216] used a PVDF/Co₃O₄ nanofiber-based TENG and a miniature Halbach magnet array for EMG to improve its electrical energy conversion efficiency. Baro et al. [217] proposed a textile-based sweat sensor incorporating a ZnO-based unipolar friction nanogenerator (STENG). Their study experimentally verified that hydrated salts in sweat promote an increase in conduction band electrons in ZnO, allowing the integrated STENG to output higher voltages. TENGs can also be integrated with flexible supercapacitors (SCs) to form a distributed power system, further enhancing the power-management capabilities of wearable devices [218]. The construction of self-charging power systems (SCPS) for TENG-SCs requires consideration of two key factors. Firstly, the AC power output by the TENG cannot be directly fed into the SC and must be converted using a rectifier. Secondly, it is difficult to share electrodes between the TENG and the SC, and alternative solutions such as shared substrates or packages are typically used [219]. These can include fabrics [220], thin films [221], carbon cloth [222,223], hydrogels [224], and others. The integration of TENGs with energy-storage technologies has led to the development of uninterrupted power supply (UPS) systems for wearable devices [225]. These systems provide a viable solution for the continuous power supply of wearable devices.

Solar Power: Singh et al. [226] installed a solar panel on top of a sweat sensor in the form of a smart watch to collect energy. A circular solar panel with a diameter of 2.2 inches was mounted on the top of the device as an energy source to power the integrated circuit of the smart watch. This combination provides a new idea for the power supply scheme of wearable devices.

Inertial Energy Harvesters: Inertial energy harvesters can convert the kinetic energy generated by human motion into electrical energy to power devices. These harvesters contain a proof mass that is excited by human motion, with the inertial energy of the motion being converted into electrical energy through piezoelectric, electrostatic, or electromagnetic methods [227,228]. To address the power density limitation imposed by the volume of the proof mass, Cai et al. [229] proposed an alternative approach. They utilized a planetary structure with a power-generating unit consisting of a base, coils, rotor, and magnets as an eccentric mass, thereby avoiding the use of a proof mass. In walking tests, the power output of this design reached 1.84 mW at the wrist and 2.95 mW at the ankle. The output of energy harvesters is influenced by factors such as the frequency of human movement and the placement of the device. To address this, Hoareau et al. [230] proposed a method for determining the optimal placement of cantilevered piezoelectric generators (PEGs). This method uses electromechanical modeling and accelerometer data to identify the optimal power source for cantilevered PEGs. According to the scenario presented in the article, the optimal placement for the device is along the axis normal to the surface of the right hand. Additionally, extremity segments such as the feet, hands, and forearms were identified as better energy sources. Beach et al. [231] compared the amount of energy harvested from the wrist, hip, ankle, and foot. Based on their analysis of the spectral content, optimal harvester parameters, and the average power output, it was concluded that the foot is able to provide more power, utilize a larger area, and exhibit a better broadband response during walking. Additionally, the foot was found to be least affected by changes in walking speed. To further improve energy harvesting, Sandhu et al. [232] proposed combining solar and kinetic energy harvesting as both energy and activity sensors.

Thermoelectricity: Thermoelectric systems convert the temperature difference (ΔT) between two interfaces into electricity. The ΔT between the human body and the environment is generally stable, making thermoelectric generators (TEGs) a promising power source for providing a stable energy supply. However, TEGs require a high temperature difference [233] or a booster [234] to provide sufficient voltage, which unfortunately reduces the flexibility of portable devices and increases the complexity of the system. To solve the issues mentioned above, fiber-based TEGs can be structurally optimized to increase the output voltage [235,236]. The all-fiber thermoelectric sensing device proposed by Qing

et al. [166] integrates the fiber-based organic electrochemical transistor (FOECT) and thermoelectric fiber (TEF). Such a power supply has sufficient output and does not require energy storage devices.

Despite promising research into self-powered modules, both biofuel cells and energy harvesters still face challenges in terms of energy efficiency, cell size, and durability. As a result, the dominance of lithium batteries remains difficult to challenge. A long-term vision and sustained efforts are required to fully transition from traditional rigid batteries to flexible power sources suitable for wearable systems.

6. Applying Machine Learning to Sweat Sensing

The trend toward multi-sensor integration is becoming mainstream, allowing in situ monitoring to provide multiple data sets simultaneously. Not only biochemical analytes, but also physical signals are rich in information. For more complex monitoring results, the right data analysis tool is critical. Machine learning has been shown in numerous medical studies [63] to be an effective tool for dealing with large and complex data sets. Machine learning is currently widely used in data analysis, image processing, etc. It can perform feature extraction, pattern recognition, and other operations. Consequently, machine learning can be combined with wearable sweat sensors to use sensor data to create personal physical health portraits.

In particular, machine learning can help classify detection results. Support vector machines (SVM) [237], decision trees [238,239], k-nearest neighbor algorithms (KNN) [240], and other methods can help with the classification of data. Machine learning can evaluate the trend of physiological indicators based on historical data and provide the current state, such as determining the rise and fall of cortisol over time according to the change in sweat cortisol concentration [241]. The data collected by the sensor is pre-processed and can be used as training data for machine learning. Sabilla et al. [242] used Principal Component Analysis (PCA) to preprocess sensor data for dimensionality reduction. Then, three machine learning methods (SVM, decision tree, and KNN) were tested to discriminate individual gender based on sweat composition. After comparison, it was found that SVM could complete the judgment with the best accuracy rate (94.12%).

Machine learning can also predict the trend of indicator changes and the probability of events occurring, as well as detect the occurrence of events. Regression methods are often used to predict changes in physiological parameters. Sankhala et al. [243] used machine learning methods to optimize the signal obtained from a sweat sensor. Data sets included impedance signals, skin temperature, and perspiration (%RH). The sensor converted the discrete input into glucose concentration, interpolated it to build a continuous signal, and then used a decision tree regression algorithm to meet the standard RMSE. The algorithm was tested on three subjects and verified to correctly capture glucose trends. The algorithm predicts the percentage of body weight loss (%BWL) using five parameters: heart rate (HR), core temperature (core T), whole-body sweat rate (WBSR), regional sweat rate (RSR), and sweat sodium ion content. The sweat sensing platform developed by Lafaye et al. [244] also uses machine learning algorithms (linear regression, LR) for prediction. The algorithm predicts the percentage of body weight loss (%BWL) using five parameters: heart rate (HR), core temperature (core T), whole-body sweat rate (WBSR), regional sweat rate (RSR), and sweat sodium ion content. Studies have shown that multimodal analysis using machine learning prediction can effectively increase the detection limit of sensing systems [245]. In addition to its predictive capabilities, machine learning can also identify events that have already occurred. For example, it can be applied in the detection of dehydration state [246] and has the ability to estimate the amount of sweating [247] throughout the body.

For optical sensing, image processing algorithms can be used to quantify colorimetric or fluorescence results. Baker et al. [195,248] developed smartphone applications using digital image processing algorithms. After acquiring colorimetric images of wearable microfluidic patches, the algorithm could perform real-time analysis under different directions

and lighting conditions, and provide quantified sweat rate and chloride concentration. This approach can be applied in recreational sports testing.

7. Challenges and Solutions

7.1. Contamination

Sweat sensors must fit closely to the human skin. However, oils and proteins from sweat, skin, beverages, and food debris outside the body can easily remain in the device, reducing its sensing performance. There are many solutions to the problem of fouling residues in electrochemical sensors, such as fluorination and electrode layering [249] or chemical modification [250]. In the field of colorimetric sensors, this problem is relatively ignored [251].

In response to the contamination problem of textile sensors, a fluorine-containing polymer can be introduced on their surface to change the wettability of the fabrics [252]. Based on this, Zhao et al. [251] studied the contamination treatment of fabric colorimetric sensors and proposed a solution. Using the piCVD method, the colorimetric array is encapsulated with a thin conformal coating of fluorinated hydrophobic polymer (Figure 5a). The coating prevents dirt from adhering to the surface of the array. Sensors produced with this technique are protected against contamination from various liquids, such as milk, coffee, and olive oil. In the same study, to overcome the interference of fabric texture on image processing, image-sharpening technology was applied during processing to ensure the accuracy of sensor identification of different pH values.

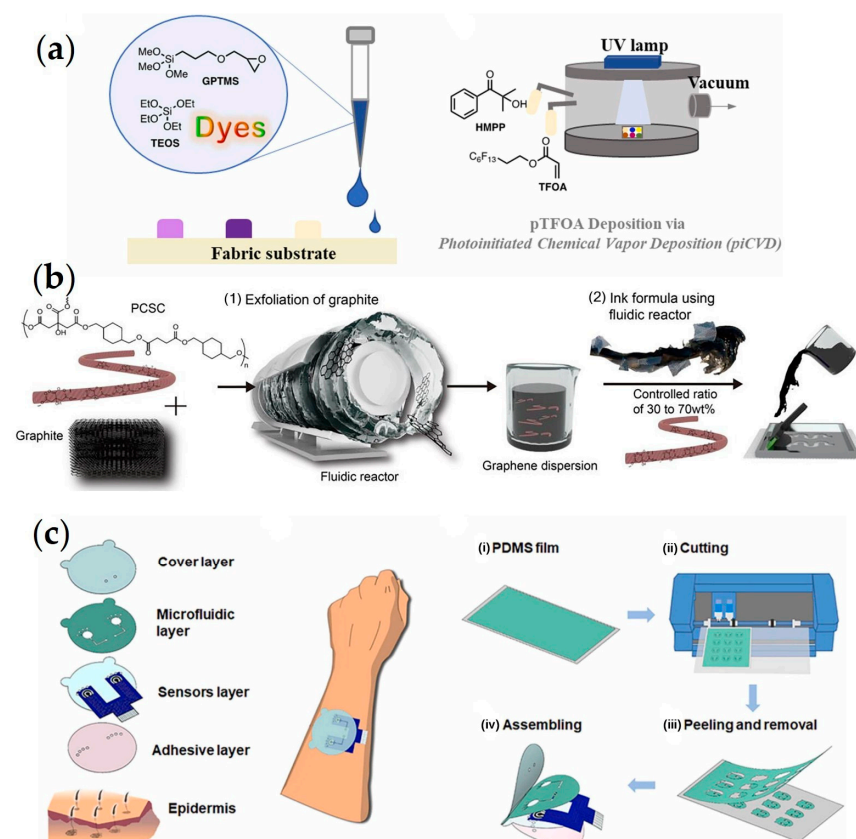


Figure 5. (a) Contamination treatment for fabric sensors. Using piCVD with fluorinated hydrophobic polymers as conformal coatings prevents dirt from remaining on the surface. Reprinted from ref. [251], Copyright (2023), with permission from Elsevier. (b) Fabrication process of the self-healing P-Gr ink and its screen-printing application. Reprinted from ref. [253], Copyright (2023), with permission from Elsevier. (c) Exploded view of the device fabricated by CAP technology and schematics of the fabrication process including four steps. Reprinted from ref. [121], Copyright (2022), with permission from Elsevier.

One approach to managing contamination is to treat it after it enters the system, through processes such as cleaning and retention prevention. Another effective option is to block contaminants at the point of sweat collection. Yang et al. [191] proposed a pH sensor with a paper-based sandwich structure based on oil control paper. After control experiments (compared with monolayer filter paper) and sample analysis, the paper-based sensor has obvious resistance to triglycerides and squalene, and can filter more than 90% of sebum in sweat. The simplicity of this microchannel manufacturing process, requiring only scissors and paper, further demonstrates the potential for practical applications. Huang et al. [254] integrated a microfilter at the entrance of the microchannel, which blocks skin debris through ten continuously arranged micropillars, thereby realizing the filtering function.

7.2. Interference

Waterproof: The operating environment of a wearable sweat sensor is determined by the wearer. If the wearer is exposed to rain, splashes, or underwater activities, the device's water resistance, adhesive stability, and resistance to contamination may be more demanding. Reeder et al. [255] previously proposed a waterproof microfluidic patch sensor. The design included a low-permeability polymer shell, a water-resistant microchannel inlet and outlet, conformal technology to reduce the effects of shear stress, underwater bonding materials, and other targeted proposals to improve water resistance.

Optical Crosstalk: Photoelectrochemical sweat sensor measurements can be affected by incomplete sweat coverage and are highly dependent on light intensity. As a result, they are susceptible to interference from vibrations caused by human movement and battery depletion. Amphoteric Bi_2O_3 has been reported to overcome these challenges [256].

Flow Rate Crosstalk: Based on current research, Komkova et al. [257] investigated the effect of sweat flow on sensor parameters, such as sensitivity. They made recommendations for addressing this issue, including flow correction, potentiostat control, and pulse detection.

7.3. Self-Healing Ability

Wearable devices must remain attached to the human epidermis during daily activities. These activities can cause deformation of the substrate and impacts to the device. Both deformation and impacts can potentially cause damage to the device. As a result, if the device possesses self-healing capabilities, it could significantly improve the lifespan, reliability, and stability of the wearable device. In this direction, there have been some new explorations, and one option is to use composite gel materials. Wang et al. [142] developed a hydrogel patch that detects sweat in situ without sweat collection. Polyvinyl alcohol and sucrose are crosslinked to form hydrogel, the self-healing adhesive properties of which are derived from hydrogen bonds between molecules. Its self-healing ability is also used to enable the autonomous assembling of colorimetric modules and substrates. Son et al. [253] prepared a P-Gr ink using a self-healing bio-based elastomer matrix incorporated with graphene (Figure 5b). This ink was used to print a conductive electrode with self-healing capabilities. These developments represent potential avenues for further research.

7.4. Technology

The complexity and high cost of manufacturing processes are among the major factors limiting the market availability of wearable sensing devices. To reduce production costs, existing methods such as paper-based fabrication, 3D printing, laser engraving, inkjet printing, and integrated circuit processes have been employed. In addition, researchers have developed new technologies specifically for wearable devices. These include the vacuum filtration transfer printing method (PS-VFTP), inspired by the photosensitive seal (PS) proposed by Hao et al. [258], and the cut and paste (CAP) technology used by Sun et al. [121] in the fabrication of wearable devices (Figure 5c). Further exploration is necessary to identify manufacturing processes that are universally applicable to the production of

wearable sweat sensors. Figure 6 provides an overview of the current challenges and potential solutions in the development of wearable sweat sensors.

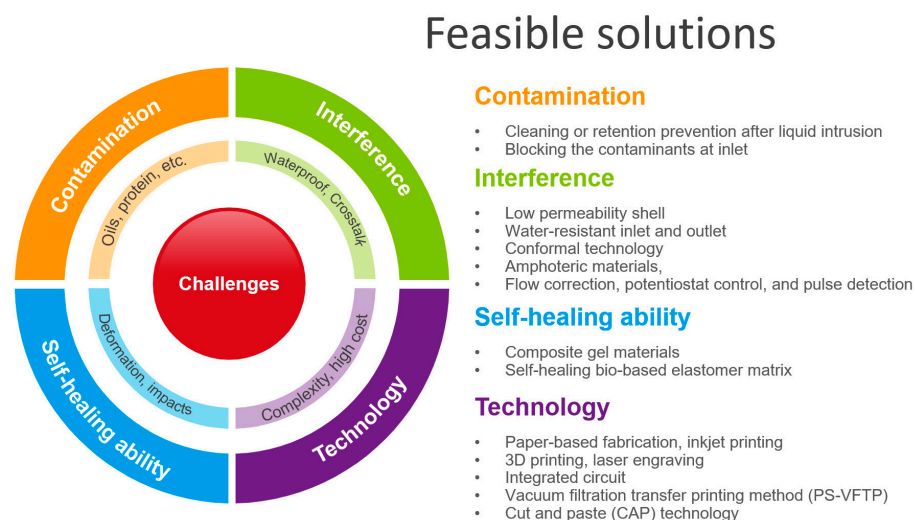


Figure 6. A summary diagram of the current challenges in wearable sweat-sensor research, along with a list of feasible solutions.

8. Conclusions

Wearable sweat sensors have drawn increasing attention due to their portability, flexibility, non-invasiveness, and ability to provide continuous real-time monitoring. Studies in this multidisciplinary research area span a range of theoretical and engineering disciplines, including biomedical principles, materials science, chemistry, physics, and electrical engineering. Distinctive advances have been made in each of these directions. This paper provides an overview of recent advances in biomarkers, sensing strategies, materials, and system architectures for wearable sweat sensors. It also summarizes current challenges and potential solutions in this field, with the aim of providing researchers with a comprehensive perspective and targets for future development. Since their inception, wearable sweat sensors have made significant advances in both form and function for practical applications. Current research is focused on the development of full-system sensors—devices capable of independently performing the entire process of sensing, signal processing and transmission, power supply, and data analysis. This represents the product form closest to practical application. In the future, it is expected that wearable sweat-sensor systems will continue to improve and new types of sensors will emerge. All of these innovative efforts will hopefully make the detection of human physiological signals more scientific and feasible.

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