Sensors & Diagnostics

This article can be cited before page numbers have been issued, to do this please use: P. Bavafa, Y. Sorkhe, L. Stanciu and A. Uzunolu, *Sens. Diagn.*, 2025, DOI: 10.1039/D5SD00221D.

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DOI: 10.1039/D5SD00221D

Fabrication Methods and Applications of Printed Wearable Sensors for Real-time Sweat Analysis: A Comprehensive Review

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Abstract

Sweat analysis has emerged as a new approach for non-invasive and continuous health monitoring. One of the significant advances in non-invasive sweat analysis has been leveraged by the implementation of printing technologies in electrochemical (bio)sensors. This in-depth review analyzes the fast-changing landscape of these cutting-edge sensors, emphasizing their strong potential to deliver continuous, real-time health information conveniently and affordably. We thoroughly examined various printing methods, including screen printing, inkjet printing, 3D printing, laser printing, roll-to-roll printing, and electrohydrodynamic jet printing, for the fabrication of the sweat sensors. In addition, an extensive section examines electrode and substrate materials, ranging from conventional carbon-based and metallic materials to advanced nanomaterials and conductive polymers. We also evaluated the shift from traditional carbon and metallic electrodes to advanced nanomaterials. A detailed assessment of recent progress in the detection of critical analytes such as glucose, lactate, electrolytes, cortisol, and other ions across fitness and sports tracking, disease management, workplace health and safety, and personalized medicine. The last portion of the paper is devoted to unraveling the challenges against practical and commercial adaptation: long-term stability, sensitivity, and selectivity in complex bio-environments, and integration with communication technologies.

Keywords: biosensors, wearable sensors, sweat analysis, electrochemical sensors, printed electrodes

1. Introduction

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The development of high-performance (bio)sensors has pushed the boundaries of detection for a wide range of analytes, especially in healthcare, biology, and chemistry, thanks to their fast, sensitive, reliable, cost-effective, and easy-to-use nature. The main working principle of a biosensor relies on the interaction of analytes with the sensor surface, which produces measurable signals from a physicochemical transducer. Continuous biomarker detection is of great interest in some cases; a well-known example is the continuous monitoring of glucose level. The advent of (bio)sensor technology has ushered in a new era, especially in healthcare applications, for detecting biomarkers associated with diseases, driven by the discovery of innovative electrode materials and the development of scalable, low-cost, and reproducible electrode fabrication methods. The development of flexible and wearable analytical devices has leveraged the point of care (POC) sensors for the skin-interface related diagnosis method, eliminating the requirement of expensive laboratory equipment [1] In addition, skin-interfaced wearable sensors enable biomarker detection via a noninvasive approach with a small or limited sample volume. The integration of wearable analytical devices with microfluidics has emerged as a next-generation sensor design enabling continuous, real-time data collection[2]. Another significant breakthrough was achieved when those next-generation sensors were integrated with wireless or Bluetooth devices, which transmit the collected data to mobile applications.

Sweat analysis is a promising non-invasive technique for real-time monitoring of various physiological measures and biomarkers [3,4]. Compared with traditional biofluids such as urine and blood, sweat sampling is minimally painful, easy to perform, and can be continuously monitored without requiring highly trained personnel [5] The complex composition of sweat, including electrolytes, metabolites, proteins, and other biomolecules, can be used to assess hydration status, electrolyte homeostasis, metabolic disease, and some biomarkers associated with diseases or physiological conditions. For example, elevated sweat chloride can be used to diagnose cystic fibrosis, sweat glucose can support non-invasive diabetes monitoring, and sweat sodium and potassium reflect dehydration or renal dysfunction[6–8]. In addition, some proteins and peptides in sweat composition may serve as biomarkers for detrimental conditions, including atopic dermatitis or psoriasis[9]. Sweat analysis also enables drug abuse testing, therapeutic drug monitoring, early cancer biomarker discovery, stress assessment via cortisol, and VOC-based screening for diseases, including tuberculosis and lung cancer [10–13]

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In recent years, a great effort has been devoted to developing innovative wearable sensors capable of measuring analytes in sweat, such as lactate[13], Ca^{2+}, glucose[14], cortisol[15], sodium[15,16], potassium[16], chloride[17,18], uric acid [19], and heavy metals[20]. Electrochemical (bio)sensors have shown exceptional promise due to their high sensitivity, selectivity, miniaturization, and compatibility with wearable platforms [8–10]. While screen-printing, photolithography, and micromachining techniques have been widely exploited in sensor fabrication, the advent of printing technologies has revolutionized the field, enabling rapid prototyping, cost-effective manufacturing, and scalable production of highly customized, flexible sensor designs [21,22].

Printing techniques, such as inkjet printing, screen printing, and 3D printing, offer unique advantages, including precise material deposition, compatibility with a wide range of functional inks (e.g., conductive, semiconductive, and insulating), and the ability to create complex patterns and architectures on substrates[15,16,23]. Over the past decade, extensive research efforts have been dedicated to developing printed electrochemical (bio)sensors for sweat analysis, leveraging various printing methodologies and material combinations[16,17]. Printed electrochemical (bio)sensors have been successfully applied to measure electrolytes, metabolites, and disease-related biomarkers in sweat [20,24,25].

Despite the progress in sweat analysis using printed electrodes, there is no dedicated review focusing specifically on printed sweat sensors. The published reviews are dedicated to wearable biosensors, electrochemical sensors, or sweat sampling with a broad scope [14,21,22,24,26]. The literature on printed sensors for sweat analysis is fragmented, with research scattered across various journals, making it difficult for researchers and practitioners to gain a holistic understanding of the field and identify emerging trends [5,15,22]. This review addresses that gap by systematically summarizing printed electrochemical (bio)sensors for sweat analysis, critically evaluating the state-of-the-art, and outlining key challenges, limitations, and future research directions.

Figure 1 (a) summarizes the fundamental components and research directions involved in the development of printed sweat sensing platforms. Sweat has emerged as a highly attractive biofluid for non-invasive health monitoring because it contains numerous physiologically relevant biomarkers, including electrolytes (Na^+, K^+, Cl^-), metabolites (glucose, lactate), hormones, and trace elements that reflect metabolic status and hydration levels [27–29]. Continuous monitoring of these analytes using wearable sweat sensors provides valuable

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insights into human physiology and personalized healthcare applications [30,31]. Flexible electrochemical sensing technologies are particularly well suited for such applications due to their high sensitivity, rapid response, miniaturization capability, and compatibility with wearable electronics [32,33]. Early developments in sweat sensing focused primarily on electrochemical detection of individual biomarkers; however, recent advances have enabled multiplexed sensing platforms capable of simultaneously detecting multiple analytes in real time. These systems typically combine flexible substrates, microelectronic signal processing units, and wireless communication modules to create fully integrated wearable health monitoring devices [34–37]. As illustrated in the schematic, the design of printed sweat sensors therefore involves a multidisciplinary integration of materials science, electrochemistry, microfluidics, and biomedical engineering [27,29,38,39].

Another key aspect highlighted in Fig. 1 (a) is the combination of sweat collection methods, printing technologies, and electrode materials that determine the overall performance of wearable sweat sensors. Sweat sampling can occur naturally during physical activity or can be actively induced using iontophoresis to enable controlled sweat extraction without exercise [33,40] Efficient sampling strategies are frequently combined with microfluidic systems that guide sweat toward sensing electrodes and allow continuous monitoring of analytes with minimal sample volumes [41,42]. From a fabrication perspective, printing techniques such as screen printing, inkjet printing, and aerosol jet printing have become dominant approaches because they enable scalable, low-cost manufacturing of flexible electrochemical sensors on substrates such as PET, PDMS, or textiles [33,41]. Screen-printed electrodes are particularly attractive since their composition can be easily tuned using conductive inks containing carbon, metals, enzymes, nanomaterials, or conductive polymers, enabling highly customizable sensing interfaces. Despite rapid progress, several challenges remain for practical deployment of sweat sensing devices, including variability in sweat composition, motion artifacts during on-body measurements, interference from coexisting biomolecules, and the need for standardized calibration and regulatory validation [2,29,40]. Consequently, current research efforts are increasingly focused on improving reproducibility, integrating microfluidics and electronics into wearable patches, and advancing large-scale manufacturing strategies to enable clinical translation of printed sweat sensing technologies for personalized diagnostics and health monitoring [43–46].

Over the past two decades, the field of sweat sensing has progressed from laboratory-based electrochemical detection to fully integrated wearable sensing platforms [30,46]. Early studies

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primarily focused on conventional electrodes and in vitro measurements of electrolyte biomarkers[47,48]. With the emergence of printing technologies such as screen printing, inkjet printing, and aerosol jet printing, flexible and low-cost sensors capable of detecting a broader range of analytes have been developed[47–49]. More recently, advances in microfluidics, nanomaterials, and wireless electronics have enabled the development of wearable systems capable of real-time monitoring of biomarkers directly on the human body[5,5,30,49,50] .Figure 1 summarizes the evolution of printed wearable sweat sensors and highlights the future roadmap toward clinically validated wearable diagnostic platforms.

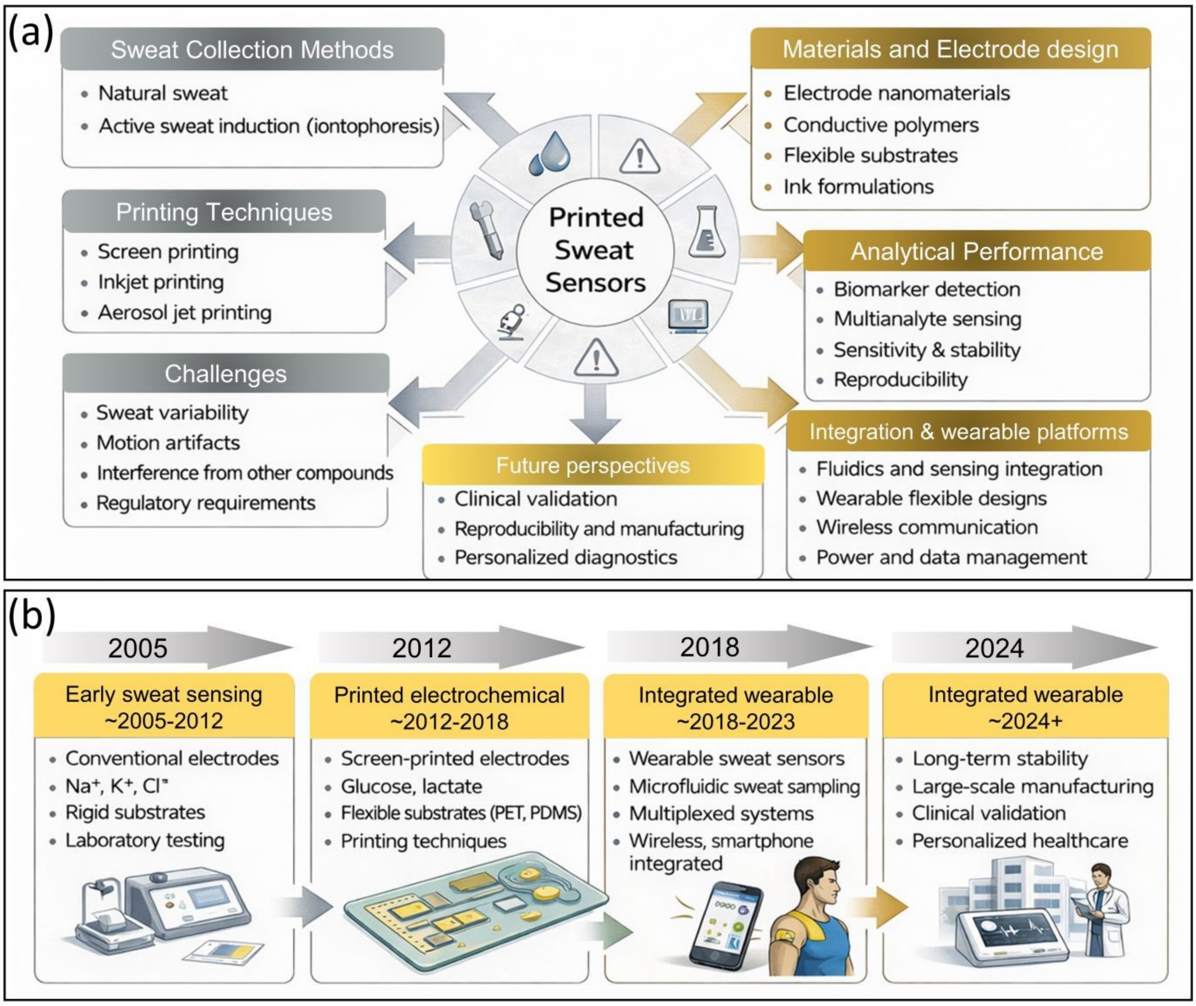

Figure 1. (a) Schematic overview of the key components in printed sweat sensor research, including sweat collection strategies, printing techniques, materials and electrode design, analytical performance, wearable system integration, current challenges, and future research directions. (b) Timeline illustrating the evolution of sweat sensing technologies from early laboratory-based electrochemical detection, through printed electrochemical sensors, to integrated wearable platforms, and the emerging phase of clinically validated wearable diagnostics.

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2. Sweat as a biofluid

Sweat is a promising biofluid for continuous, real-time health monitoring outside the skin due to its rich biomarker content of electrolytes, metabolites, proteins, and hormones [51,52]. Unlike blood or interstitial fluid, sweat can be collected without invasive procedures, enabling continuous, real-time wearable-based health monitoring [3]. Moreover, its non-invasive nature offers excellent potential for various applications, ranging from sports physiology, where it is beneficial for balancing electrolyte status, to clinical diagnosis, such as measuring chloride content for cystic fibrosis screening in neonates. Advances in wearable and microfluidic sensor technology have propelled the potential for correct determination of sweat composition and reporting on physiological as well as pathological status [53,54].

2.1. Sweat collection method

The integrity and composition of the collected sweat sample are among the main concerns, as they are influenced by the sweat collection method; deviations in the results may occur. Moreover, any contaminant introduced during sample collection may alter the actual analyte concentrations [55]. The technique of sweat stimulation, whether through exercise, iontophoresis, or passive collection, can affect sweat rate and composition [7]. Exercise-induced sweat, for instance, may have different electrolyte concentrations than in the resting state due to physiological changes during physical activity. Furthermore, the material used for sweat collection can also affect results; some materials may adsorb specific analytes or leach substances into the sample, leading to false measurements [10]. Temporal factors also play a role, as sweat composition can change over time due to evaporation, leading to the concentration of some analytes and the potential loss of volatile components [56]. The skin's microbiome can metabolize specific sweat components, altering sample composition if not promptly analyzed or properly preserved [57].

Additionally, the anatomical site of sweat collection can influence results due to variations in sweat gland density and local skin chemistry across different body regions [58]. Sample processing techniques, such as centrifugation or filtration, may inadvertently remove or alter specific analytes, particularly larger molecules like proteins or cellular components [59]. Storage conditions and the time between collection and analysis can lead to the degradation of unstable compounds or the growth of microorganisms, further altering the sample composition [60]. Lastly, the analytical method itself, including sample preparation steps such as dilution or extraction, can introduce variability and potentially change the original composition of the sweat sample [56]. Understanding and addressing these factors is crucial to developing standardized protocols that ensure accurate and reliable sweat analysis. A detailed examination of the sample collection methods is described below.

2.1.1. Active Method

The active method involves stimulating the skin to produce sweat and is usually done through two main techniques: i) in the exercise-induced sweating technique, physical activity increases sweat production due to the body's need to regulate temperature. This method is non-invasive and natural, but it can be challenging to control the exact amount of sweat produced and may not be suitable for all users [61]. ii) In the chemical induction (iontophoresis) technique, chemical agents like pilocarpine are used to produce the sweat. This agent, with the help of a mild electrical current, penetrates the skin and stimulates sweat glands [62]. It is more precise than exercise-induced sweating and allows control over the amount of sweat produced, but it may cause skin irritation. Active sweat-collection methods have been used in printed biosensors for monitoring various analytes, including electrolytes, metabolites, and hormones [26]. For instance, Gao et al. [4] developed a fully printed biosensor for monitoring glucose and pH levels in sweat, utilizing an active sweat-collection method via pilocarpine-induced iontophoresis.

2.1.2. Passive Method

Passive sweat collection relies on the body's natural sweating without external stimulation. This method typically involves wearing absorbent patches or materials that collect sweat as it is naturally produced [26]. Absorbent patches directly absorb sweat from the skin's surface and transfer it to the sensor for analysis. These patches need to be waterproof, comfortable, and able to absorb sufficient sweat [63]. While these patches offer the advantage of comfortable long-term wear and require no additional equipment, their effectiveness in regulating sweat production can be inconsistent. This variability stems from individual physiological differences and fluctuations in environmental conditions, making it difficult to control sweat levels precisely. Passive sweat collection methods have also been widely employed in biosensors, offering a non-invasive, continuous-monitoring approach [64]. Researchers at the University of California, Berkeley, have developed a printed biosensor array capable of monitoring multiple biomarkers in sweat, including chloride, glucose, and lactate, using a passive sweat collection approach [65]. Gao et al.[4] presented a fully printed biosensor patch for

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simultaneous monitoring of multiple biomarkers in sweat, utilizing passive sweat collection and screen-printed electrodes.

2.1.3. Microfluidic Method

Wearable sensors often incorporate microfluidic systems that use networks of microscopic channels to direct and collect sweat for precise analysis. These devices leverage capillary action or other microfluidic principles to guide sweat to the sensing area [20]. This method offers several advantages: precise control over sweat volume, the ability to detect multiple analytes simultaneously, and reduced risk of environmental contamination [66]. As a result, microfluidic-based sensors typically provide higher accuracy and sensitivity. However, this approach also has drawbacks: complex design and manufacturing processes can lead to higher production costs and may require sophisticated technology for implementation. The microfluidic method can be combined with printed biosensors to enable highly sensitive and multiplexed analysis. For example, Emaminejad et al. [67] introduced a fully integrated microfluidic sweat biosensor system featuring printed electrodes and microfluidic channels, capable of simultaneously monitoring multiple analytes, including glucose, lactate, and pH. Koh et al. [4] developed a printed electrochemical biosensor integrated with a microfluidic sweat collection system for continuous monitoring of lactate levels during exercise.

Furthermore, researchers have explored combining different sweat collection methods to enhance the performance and reliability of printed biosensors. For instance, Munje et al. [68] proposed a hybrid approach that combines passive and active sweat-collection techniques for continuous monitoring of glucose and pH levels in sweat using a printed biosensor system. Sweat collection methods and their pros and cons are summarized in Figure 2. The active, passive, and microfluidic sweat-collection methods have been extensively employed in the printed biosensors, each offering unique advantages and applications. The choice of sweat collection method depends on factors such as the target analyte, desired monitoring duration, and the specific requirements of the biosensor system. Ongoing research aims to further optimize and integrate these sweat-collection techniques with printed biosensors, enabling more accurate, reliable, and continuous monitoring of biomarkers for personalized healthcare and sports performance.

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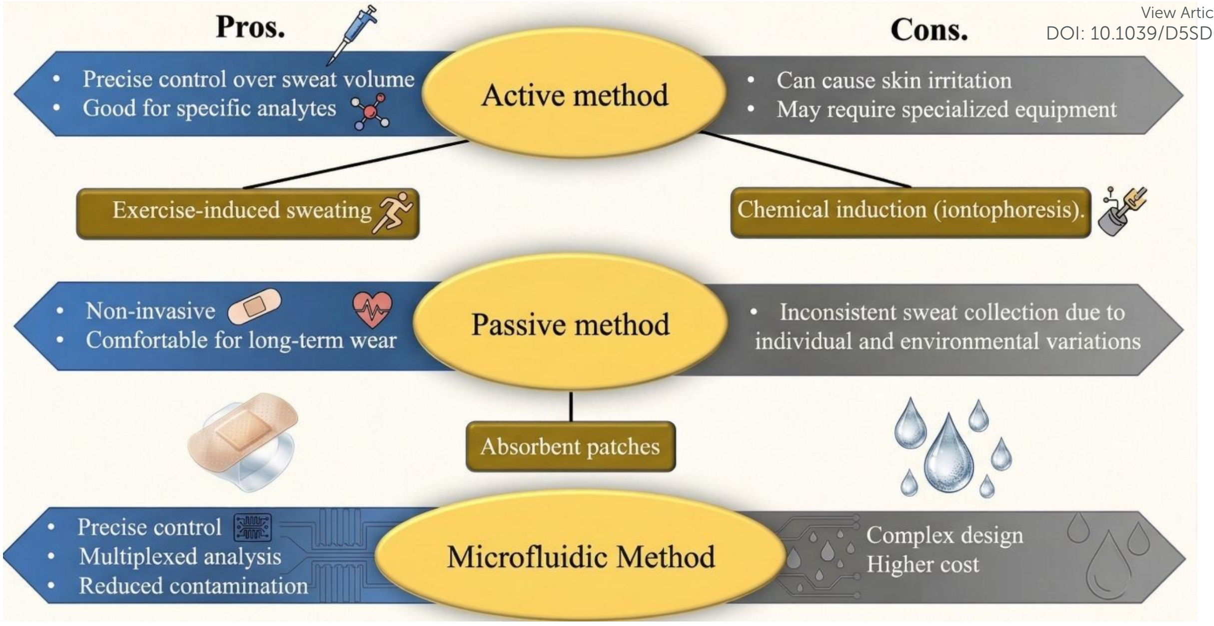

Figure 2. Sweat collection methods and their advantages and disadvantages.

3. Printed Electrochemical Biosensors

3.1. Printing Methods for Electrochemical Sensor Fabrication

Printing methods have been widely used in the production of electrochemical sensors and biosensors owing to their ability to fabricate miniaturized, inexpensive, and repeatable devices [69]. It involves the controlled deposition of functional materials (e.g., conductive inks, enzymes, or other biomaterials) onto a substrate. Table 1 lists the significant ink properties of five typical printing processes: screen, gravure, inkjet, flexography, and offset. Gravure and inkjet printing processes use low-viscosity inks with tiny particles to facilitate precise jetting, whereas screen and offset printing processes use much thicker, high-viscosity inks [14,70,71]. While surface tension is less significant in screen printing, it is crucial in inkjet printing to ensure perfect droplet formation. While all those processes use inks containing small particles, they differ in their solids content. Inkjet and gravure printing methods use lower solid content, whereas screen and offset printing methods use higher solid content, which affects drying time and final print properties [72–74].

Table 1. Printing method, relative viscosity, surface tension, particle size, and physical characteristics of the inks.

Method	Viscosity	Surface Tension	Particle Size	Other Traits	Ref
Inkjet	Low	Medium	Very small	Fast-drying, low solids	[47–49]

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Screen Printing	Very high	Not critical	Small	High solids, thick	[75]
Gravure	Medium	Low	Very small	Fast-drying, low solids	[76]
Flexography	Medium	Medium	Small	Fast-drying, medium solids	[77]
Offset	Very high	Not critical	Small	High solids, sticky	[49,50]

3.1.1. Screen Printing

Screen printing is one of the most widely used printing methods for developing electrochemical sensors and biosensors, in which a viscous ink or paste is forced through a patterned mesh or screen onto a substrate using a squeegee blade[78,79]. Nitish Kumar et. al. [80] demonstrated the successful detection of lactate in human sweat using LDH-modified screen-printed carbon electrode (SPCEs) without the need for redox chemicals. Figure 3 visually explains how lactate is detected in their work. The process utilizes a benchtop E4980A precision LCR meter and an LDH-modified SPCE. In this process, a patterned screen or mesh, typically made of stainless steel or polyester, is formed by blocking certain areas of the mesh, while leaving the open areas for material deposition. The ink or paste is then forced through the open areas onto the substrate using a squeegee blade (Figure 4a). The final thickness and resolution of the printed pattern depend on factors such as mesh count, ink viscosity, and squeegee pressure [16,66]. Cost-effectiveness, scalability for mass production, the ability to deposit a wide range of materials (including conductive inks, enzymes, and polymers), and the ability to produce well-defined, high-resolution, reproducible patterns are among the key advantages of this method [68,81,82]. On the other hand, the limited resolution compared to other printing techniques, difficulty in depositing materials with low viscosity or high particle size, and relatively high material waste due to screen blocking are drawbacks of the screen-printed method [83,84].

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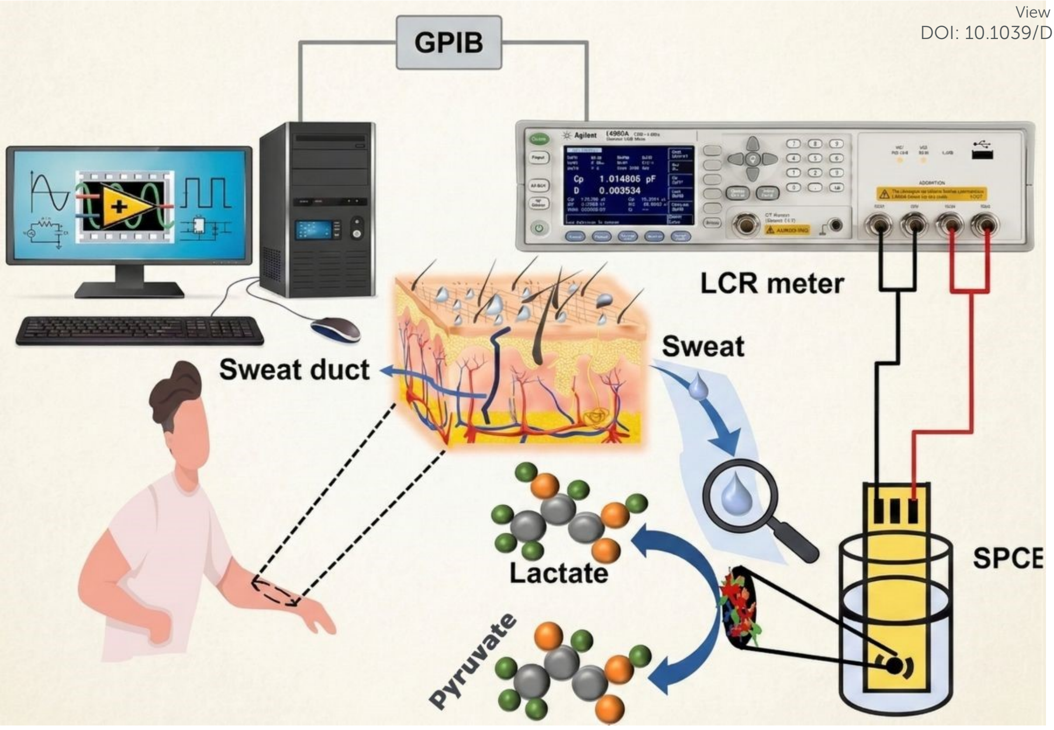

Figure 3. The process of lactate detection using a benchtop E4980A precision LCR meter and a Screen-printed carbon electrode. Reprinted with permission from [80]. Copyright (2023) Elsevier.

3.1.2. Inkjet Printing

The use of inkjet printing for biosensor fabrication has soared in recent years owing to its cost-effectiveness, ability to print on various substrates, and its minimized ink consumption. Inkjet printing is carried out by controlled deposition of drops of functional materials onto a substrate, as illustrated in Figure 4b. The most widely used inkjet printing techniques include thermal inkjet printing, in which the ink is heated to produce bubbles that eject droplets, and piezoelectric inkjet printing, in which pressure waves generated by a piezoelectric material eject droplets. Since the printed pattern is digitally controlled, droplets can be deposited precisely on the substrate, enabling high-resolution patterning [69,85]. The viscosity and surface tension of the ink should be tailored to achieve high-quality printed patterns [86,87]. Furthermore, the functional materials in the ink may cause nozzle clogging, reducing print quality and thickness [12,12,85,88].

3.1.3. Aerosol Jet Printing

Aerosol jet printing is a contactless printing technique that uses a focused beam of atomized ink drops to deposit high-resolution patterns on various substrates (Figure 4c) [14]. The method can be employed to deposit a variety of materials, from conductive inks to insulators and

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biological recognition elements, making it suitable for the production of multifunctional, multi-layered electrochemical sensors [73]. Aerosol jet printing has also been applied in sweat analysis to develop sensors to detect biomarkers such as glucose, lactate, and cortisol with selectivity and sensitivity [71,72].

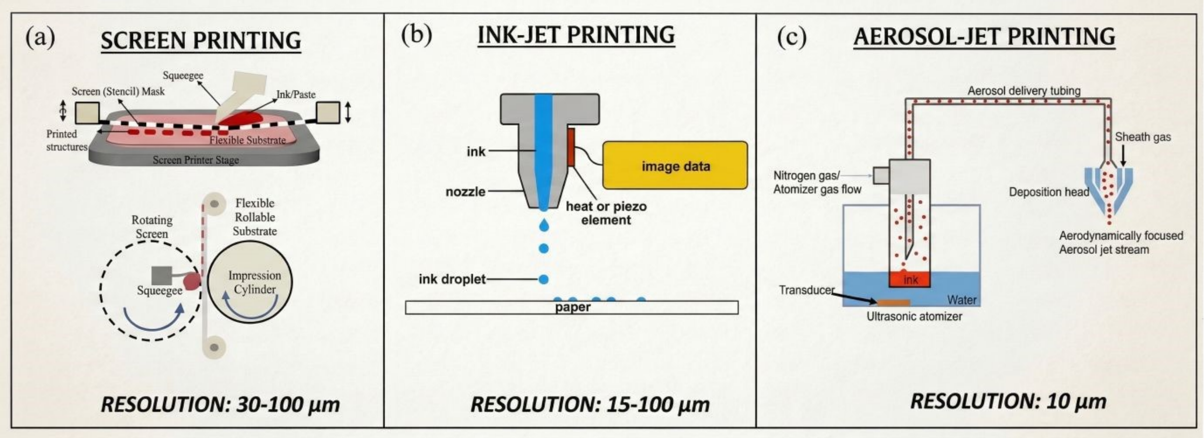

Figure 4. The schematic of (a) screen-printing, (b) inkjet printing, and (c) aerosol jet printing method. Reprinted with permission from [14].

3.1.4. 3D Printing

3D printing, also known as additive manufacturing, has proven a promising approach for fabricating electrochemical sensors and biosensors, with the potential to produce intricate, high-precision 3D structures. 3D printing methods, such as fused deposition modeling (FDM) and stereolithography (SLA), involve creating three-dimensional structures layer by layer [74,78].

Among all 3D printing processes, the FDM process, schematically shown in Figure 5(a), is widely recognized as the most popular, attributed to its simplicity, ease of operation, and low cost [16]. While in FDM, a thermoplastic is melted and squeezed out of a nozzle, a photosensitive resin is selectively cured with UV light or a laser in SLA both techniques support the creation of complex geometries as well as the integration of various functional materials, such as conductive inks, enzymes, and polymers, into the printed architecture [16,89–92]. Ability to construct complex 3D structures and geometries [93], shape flexibility and rapid prototyping, integration of multiple materials and functionalities in a single device, minimal material loss, and cost-effectiveness for small-scale production are among the advantages of the 3D printing method. However, a limited range of compatible materials, especially conductive inks and biological components, and relatively low printing rates for mass production are disadvantages of the 3D printing method.

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Apart from FDM and SLA, the direct ink writing (DIW) method, schematically depicted in Figure 5(b), is a new 3D printing technology that revolutionizes additive manufacturing by enabling one-step printing of functional inks and minimizing post-processing. DIW significantly expands 3D printing capabilities, enabling rapid prototyping and low-cost fabrication of complex, functional structures across industries [94]. The aerosol jet printing (AJP) additive manufacturing pathway used for functional ink printing is schematically illustrated in Figure 5 (c)[95]. Stereolithography (SLA) is a 3D printing technology that builds objects layer by layer using UV light to cure liquid resin. The two settings are bath and bat. Under the bath setting, a stream of UV traces a 2D cross-section on a submerged substrate submerged in a pool of liquid resin. The substrate is lowered after each layer, and a blade cuts off the top surface of the resin. The bat structure features a suspended substrate and a light source beneath the tank. The two configurations outlined schematically in Figure 5 (d) and (e) are either laser- or digital light processing (DLP)-powered for controlled photopolymerization [96,97].

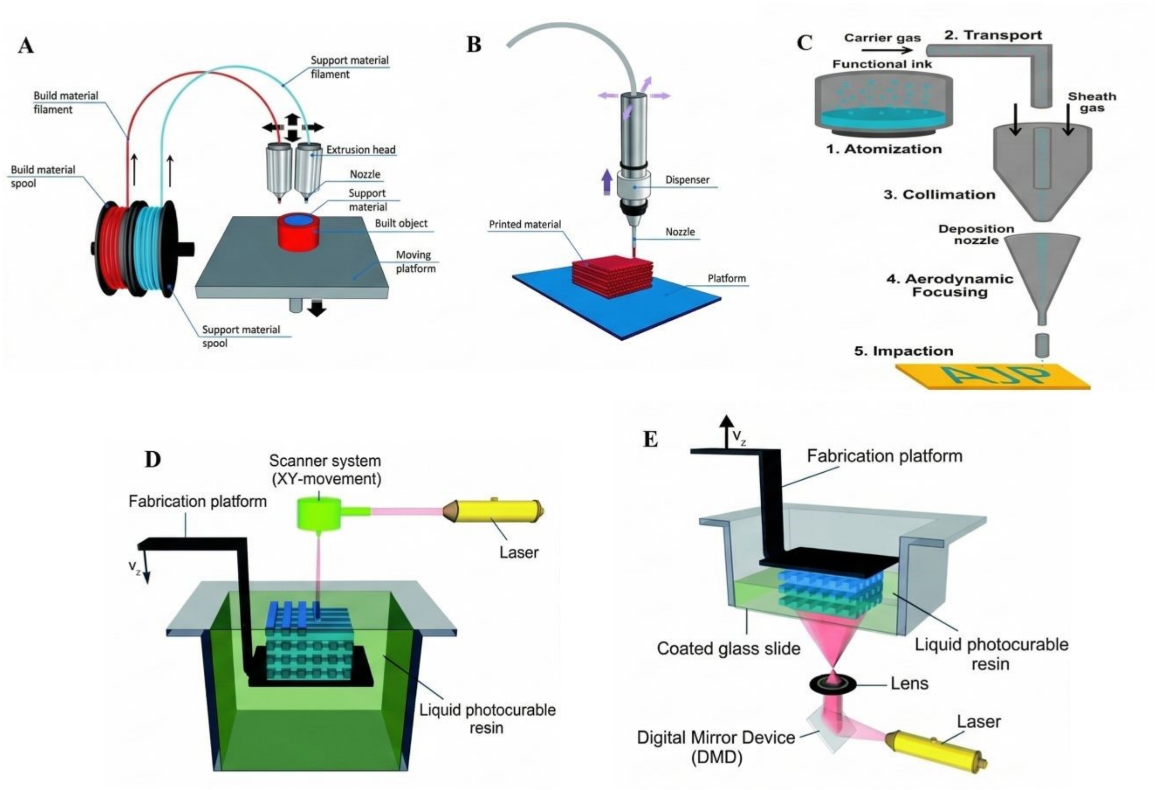

Figure 5. Schematic of the 3D printing method showing a heated nozzle precisely depositing semi-molten thermoplastic material layer by layer to build a 3D structure (a). The DIW technique uses a controlled dispenser to lay down viscous ink material in a similar layer-by-layer fashion (b). with permission from The Royal Society of Chemistry[94]. AJP additive manufacturing method for printing

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with functional ink (c). Reproduced from Ref. [95], with permission from IOP Science. Laser-scanning SL with a free surface/bath configuration (d), and DLP SLA employing a constrained-surface "bat" configuration (e), with permission from Elsevier [97]

A novel 3D-printed wearable patch was fabricated in a study by Kim et al. [98] (Figure 6). This patch incorporated a microfluidic channel and versatile ion-selective sensors, enabling in-situ monitoring of sweat electrolytes, specifically Na^+, K^+, and Ca^{2+} ions. To achieve selective detection of these target ions, ionophores made of polyvinyl chloride (PVC) were incorporated into the 3D-printed electrode. Figure 6 (a-e) shows the AIIW (all-in-one wearable) patch, which consists of two main elements. First, a flexible, 3D-printed sensing unit responsible for detecting and analyzing sweat biomarkers. Second, a flexible WMFSH (wearable microfluidic fresh sweat harvesting) unit is designed to establish seamless skin contact and efficiently collect fresh sweat for analysis. This WMFSH unit is securely attached to the skin using a skin-friendly double-sided adhesive layer, ensuring continuous sweat sampling and accurate readings by the sensing unit [98]. Figure 6 (f-h) shows two main parts of the sweatainer system: the sweatainer device itself and the epidermal port interface that connects it to the skin. The sweatainer device comprises a 3D-printed microfluidic network with enclosed channels and open reservoirs, a 200 μm-thick PDMS layer that seals the reservoirs, and a 60 μm-thick gasket made from medical-grade adhesive. It shows how it's put together and how it attaches to the skin. The sweatainer itself is a 3D printed structure with tiny channels and open areas for sweat to collect. It's sealed with a thin PDMS layer and attached to the skin using a special medical adhesive [99]. Real-time sweat monitoring with the AIIW patch is demonstrated in Figures 6 (i) and 6 (j). The patch, secured to the subject's forearm with a double-sided adhesive band, continuously tracked sodium, potassium, and calcium levels in sweat during and after exercise [98].

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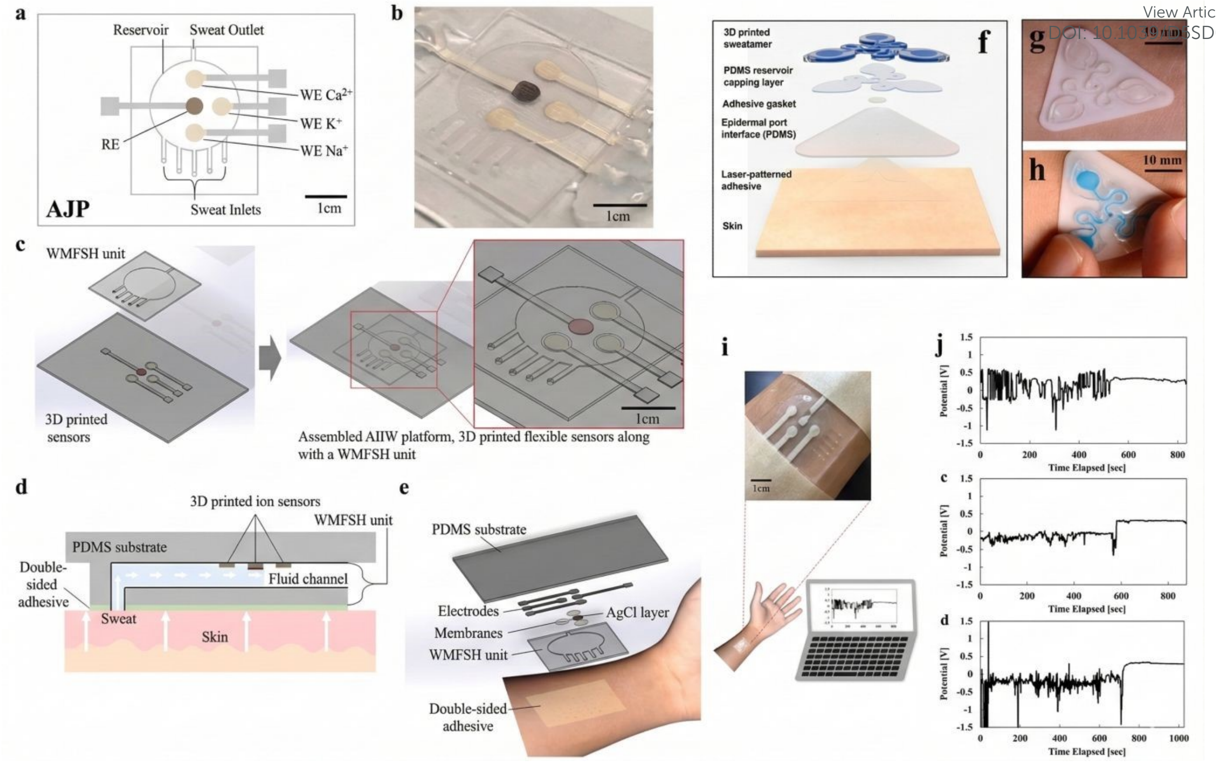

Figure 6. Schematic representation (a), an optical image of the actual device (b), its individual units (c), a cross-section illustrating its attachment to the skin (d), and a breakdown of its various components (e) [98]. An illustration of 3D printed microfluidic devices designed for epidermal sweat detection (f-h) reprinted from [99]. Real-time sweat analysis for measuring sodium, potassium, and calcium levels (i) and their relative results (j). Reprinted with permission from [98].

3.1.5. Laser Printing

Laser printing and, more specifically, laser-induced forward transfer (LIFT) have been versatile methods for fabricating electrochemical sensors for sweat analysis [100]. The LIFT principle relies on a pulsed laser that produces a localized, high-pressure zone on a donor substrate (i.e., a thin film of conductive ink), which propels a microdroplet onto a receiver substrate [100]. This enables high-resolution, accurate material deposition, suitable for creating intricate electrode patterns and sensor arrays. LIBT is performed by laser irradiation via a transparent acceptor onto a donor film on an opaque substrate. Both techniques illustrate the potential of laser-induced micro/nanofabrication for the realization of sophisticated devices [101]. In sweat analysis, LIFT has been used to deposit various conductive materials, such as silver, gold, and carbon, on flexible substrates, facilitating the development of wearable electrochemical sensors for monitoring electrolytes, metabolites, and even cortisol in sweat. Figure 7 shows the Schematic representation of the LIFT and LIBT printer working principles [101,102].

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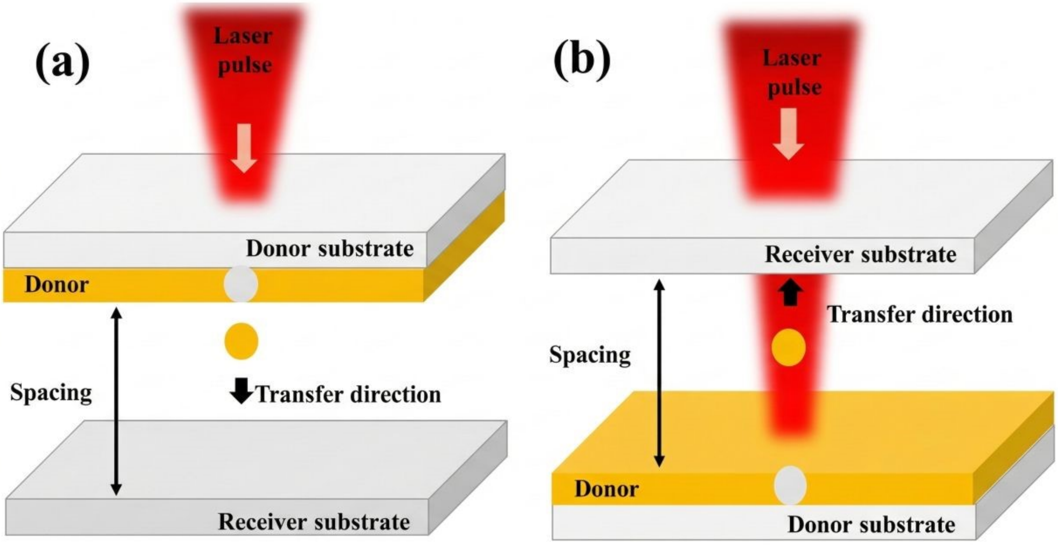

Figure 7. Schematics of setups for (a) LIFT and (b) LIBT. Reprinted with permission from [101].

3.1.6. Roll-to-Roll Printing

Roll-to-roll (R2R) printing is a high-throughput, scalable manufacturing technique used to fabricate electrochemical sensors for sweat analysis [100]. This method involves continuously feeding a flexible substrate (e.g., PET, PI) between two rollers, while functional inks are deposited using various printing techniques, such as gravure, flexography, or screen printing [103]. R2R printing enables rapid, cost-effective production of large-area sensors, making it suitable for the mass manufacturing of wearable sweat-monitoring devices. Notably, researchers have used R2R printing to fabricate sweat sensors capable of detecting glucose, lactate, and electrolytes, paving the way for personalized healthcare monitoring [100].

A schematic of the R2R printing method is shown in Figure 8 (a). A flexible PET substrate is fed through a series of processing units, including a screen-print unit, an aligner, a UV curing unit, and an oven. This process is repeated multiple times to create the biosensor's layered structure. A sample of a biosensor produced by this method is shown in Figure 8 (b). A printed patch made by the R2R method, attached to a body part, is shown in Figure 8(c). This type of printed biosensor can be used to evaluate the composition and dynamics of exercise- and iontophoretic-sweat samples. In research conducted by Nyein et al., R2R-printed biosensors were used to measure analytes in sweat and sweat rate simultaneously. These studies aim to explore the connections between sweat parameters and an individual's health or fitness level [103].

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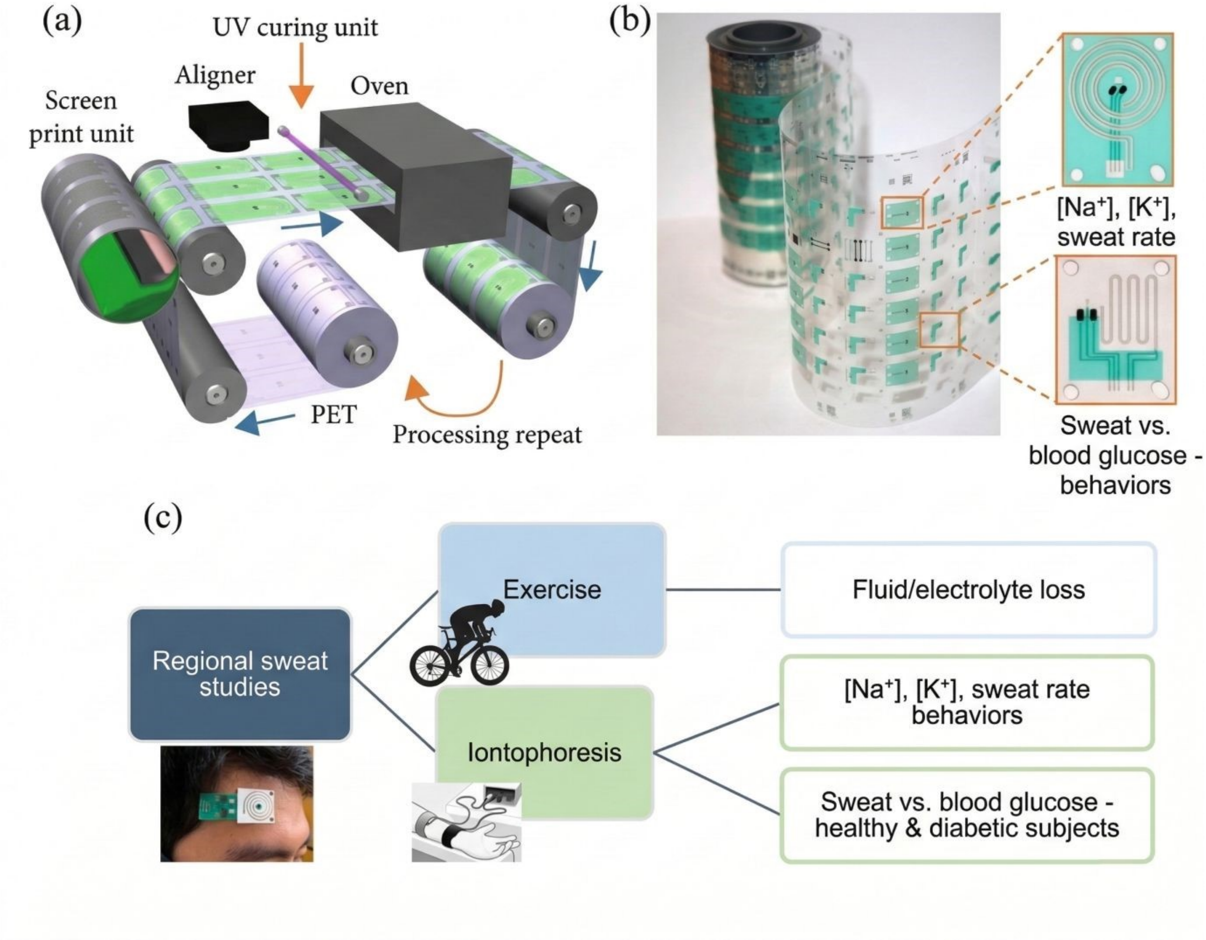

Figure 8. Schematic of roll-to-roll screen printing (a), biosensor fabricated by roll-to-roll printing method (b), and application of a printed patch attached to part of a body, which can be used to study the composition and dynamics of exercise and iontophoretic sweat [104].

3.1.7. Electrohydrodynamic Jet Printing

Electrohydrodynamic (EHD) Jet printing is a general approach that utilizes electric fields to generate and manipulate jets of functional inks onto a substrate [105]. It offers high process control and resolution and can be used to fabricate complex electrode geometries and sensor arrays. EHD printing has also been employed in sweat analysis to fabricate microfluidic channels for sweat collection and transport, as well as to print conductive ink for electrochemical sensing. This approach holds potential for the fabrication of integrated microfluidic platforms for sweat-based diagnostics [106–108] . In the EHD system depicted in Figure 9 (a) [109], a syringe pump propels silver ink towards a nozzle tip. A high DC power supply is connected to the nozzle, creating an electric field that pulls the ink into a thin jet. This is then squeezed onto a substrate placed on a translating stage to allow patterned control. A camera monitors the entire process,

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and a computer would likely control the system. This setup uses electrical control to precisely deposit silver ink, forming complex patterns on a substrate. An EHD-printed high-resolution silver dot with silver nanoparticle ink is shown in Figure 9 (b) [110]. Accurate control over printing and high resolution are the advantages of the EHD method, as shown in Figure 9(c) [111]. Microscope image of two adjacent layer of thin wall (e)[112]

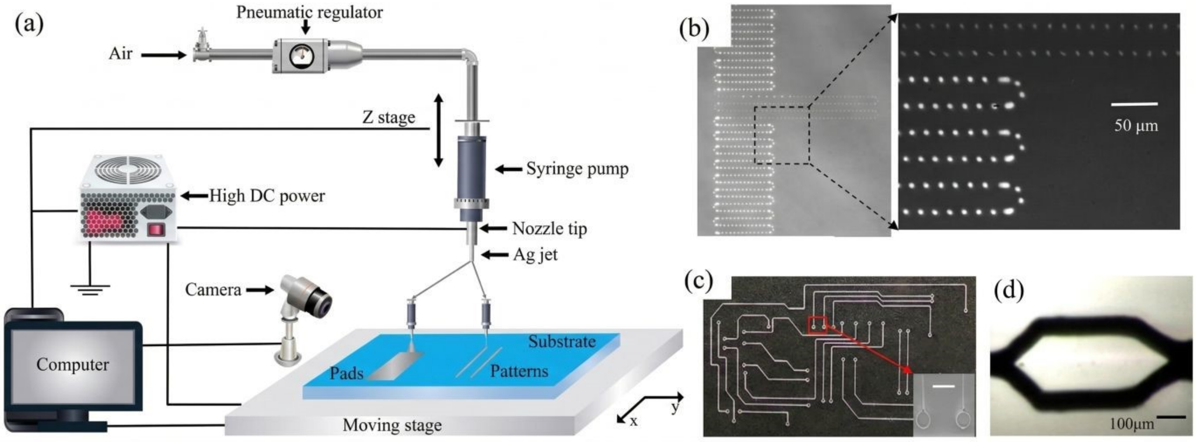

Figure 9. Schematic of EHD jet printing (a) [109], EHD printed AgNP droplet (b)[110], and EHD directly printed 2D and 3D structures using molten metal alloys (c) [111] Microscope image of two adjacent layer of thin wall (d)[112]

3.2. Electrode materials

Various electrode materials are applied in printed electrochemical (bio)sensors, and the choice is based on factors such as conductivity, electrochemical activity, and compatibility with the printing method. Carbon-based materials, such as carbon pastes, carbon nanotubes, and graphene, are traditionally used for their high electrical conductivity, low cost, and ease of printing. In addition, metal nanoparticles, such as gold, platinum, and silver, exhibit high electrocatalytic activity and are commonly used in printed electrodes to improve sensitivity and selectivity [72,74]. Flexible polymers such as poly(3,4-ethylenedioxythiophene) polystyrene sulfonate (PEDOT: PSS) and polyaniline have also been studied for their flexibility, biocompatibility, and potential for printing using a broad range of methods [16,90,92]. The selection of electrode materials is critical for the enhanced performance of printed electrochemical sensors for various applications [96,100,103] . Table 2 provides information on the functional materials and electrolytes used in printed electrochemical sweat analysis sensors, along with the printing techniques employed. While potassium chloride (KCl) and sodium chloride (NaCl) are ubiquitous electrolytes in most methods, others, such as phosphate-buffered saline (PBS)

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and artificial sweat, are also used to mimic physiological conditions (27,33,55,103). Notably, functional materials such as silver/silver chloride ink are commonly used in inkjet, laser, roll-to-roll, aerosol jet, and electrohydrodynamic jet printing, indicating their ease of use in these processes. This inconsistency in the selection of electrode and electrolyte materials is a testament to the ongoing interest in enhancing sensor performance and tailoring them for specific analytes and printing techniques [23,99,114,115].

Table 2.The electrolyte and electrode materials are used in various printing methods.

Printing Method	Electrode Materials	Electrolyte Materials
Screen Printing	Carbon[4,26,116,117] Gold [72,118] Silver [119–121] Platinum [92,122]	Potassium chloride (KCl) [4,26,116,117] sodium chloride (NaCl) [123] phosphate buffer saline (PBS) [92] artificial sweat [121] sodium sulfate (Na_2SO_4) [117]
Inkjet Printing	Silver [124–127] Gold [126,127] Carbon [128] PEDOT: PSS [129–131]	Silver/silver chloride (Ag/AgCl) ink[125,132,133] potassium chloride (KCl) [126,127] sodium chloride (NaCl) [133] phosphate buffered saline (PBS)[124,134,135] potassium nitrate (KNO_3) [21,136]
3D Printing	Carbon [137–139] Gold [140] Silver [140,141] Platinum [93,142]	aqueous electrolytes with potassium chloride (KCl) or sodium chloride (NaCl) [94,94,143]
Laser Printing	Silver [143], Gold [143], Carbon [33], Graphene [102,103]	Silver/silver chloride (Ag/AgCl) ink [144] potassium chloride (KCl) [145], sodium chloride (NaCl) [144]
Roll-to-Roll Printing	Silver [146], Gold[146], Carbon [147]	Silver/silver chloride (Ag/AgCl) ink [148] potassium chloride (KCl) [125], sodium chloride (NaCl)) [147]
Aerosol Jet Printing	Silver [149], Gold [105]	Silver/silver chloride (Ag/AgCl) ink [73,150] potassium chloride (KCl)[151] sodium chloride (NaCl) [152]
Electrohydrodynamic Jet Printing	Silver [153], Gold [154]	Silver/silver chloride (Ag/AgCl) ink [154,155] sodium chloride (NaCl) [156]

3.3. Substrate materials

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The success of the printing process depends heavily on the compatibility of the inks with the substrate surface. In addition, the choice of substrate will have a profound impact on the mechanical and thermal properties, as well as the performance, durability, and wearability of the printed electrodes. Therefore, the choice of substrate is a critical factor in the development of printed electrochemical sensors for sweat analysis [26]. Traditionally, rigid substrates such as glass, silicon, and ceramics have been used due to their excellent chemical stability and well-defined surface properties [157]. However, the growing demand for flexible and wearable sensors has shifted focus towards more pliable materials. Polymer-based substrates such as polyethylene terephthalate (PET), polyimide (PI), and polyethylene naphthalate (PEN) have gained popularity due to their flexibility, low cost, and compatibility with various printing techniques [158]. These materials enable the fabrication of conformable sensors that can adapt to the curvature of the human body, enhancing comfort and maintaining consistent skin contact [4].

In recent years, there has been increasing interest in stretchable substrates further to improve the wearability and durability of sweat sensors. Materials such as polydimethylsiloxane (PDMS) and thermoplastic polyurethane (TPU) offer excellent elasticity and biocompatibility, allowing sensors to withstand repeated deformation without compromising their performance [159]. These stretchable substrates enable the development of sensors that can accommodate the dynamic nature of human skin during movement, maintaining sensor functionality and skin contact even during physical activity [160]. The motivation for using different substrates is to tailor sensor properties to meet the requirements of specific applications. Paper-based substrates, for instance, have gained attention for their low cost, biodegradability, and potential for disposable sensors [161]. Conversely, cloth-based substrates enable the direct embedding of sensors into clothing in an unobtrusive manner, providing a convenient platform for continuous sweat monitoring [162]. In addition, the substrate properties can affect printing and the final properties of the resultant sensors. For example, some substrates require surface pretreatments and the use of primers to enhance adhesion and the uniformity of printed layers [163]. Thermal and chemical stability of the substrate should also be considered, particularly when post-processing at high temperatures is used, or the sensor is exposed to various chemical environments in sweat [8].

Briefly, the selection of substrate material plays a vital role in the flexibility, stretchability, biocompatibility, chemical resistance, and printability of the printed sensors. With advancements in the field, new substrate materials and composites continue to be developed to

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meet the evolving demands of wearable sweat-sensing technology, pushing the boundaries of sensor performance and wearer comfort [164].

4. Printed electrochemical (bio)sensors for sweat analysis

Table 3 summarizes various studies on printed electrochemical sensors for sweat analysis. It encompasses a range of printing methods, including laser scribing, screen printing, inkjet printing, and 3D printing. The analytes detected by these sensors vary widely, from ions such as sodium, potassium, and chloride to metabolites such as glucose and lactate, and even complex biomolecules such as cortisol. The substrate materials used for printing also vary, including polyethylene terephthalate (PET), polydimethylsiloxane (PDMS), PVC paper, nonwoven cloth, and even stretchable substrates. The table highlights the diverse applications of those printed sensors, ranging from hydration status assessment and disease diagnosis for athlete performance monitoring to drug detection. It also showcases the versatility of printing technologies in fabricating wearable sensors with integrated features like microfluidics, wireless communication, and energy harvesting. However, the table also reveals some of the challenges in this field, such as the need for improved sensitivity and stability of printed sensors, especially under mechanical stress and in complex biological fluids. Additionally, integrating multiple functionalities into a single device while maintaining miniaturization and wearability remains an ongoing area of research.

Table 3.Summary of the recent investigation on the printing method for sweat analysis.

Printing method	Analyte type	Substrate materials	Ink material	Main focus of the paper	References
Laser scribing	H_2O_2	Polyimide	-	Wearable sweat-capture device with patterned graphene arrays	165
Screen printing	K^+, Na^+	Polyethylene terephthalate (PET)	Ag/AgCl, carbon, insulator inks	Sweat sensor for assessing hydration status	166
Screen printing	Creatinine, urea, pH	Polydimethylsiloxane (PDMS)	-	Passive sweat collection and colorimetric analysis	3
Screen printing	Glucose	PVC paper	Carbon ink, MXene/NiSm-LDH	Enzyme-free electrochemical glucose sensor	167
Screen printing					168
Screen printing/heat-transfer	Cl^-, Na^+, K^+, NH^{4+}	PET, nonwoven cloth	Carbon, silver, resist inks	Wearable ion sensor for sweat monitoring	169
Screen printing	Na^+, NH^{4+}, lactate	Polyethylene terephthalate (PET)	Gold nanoparticle, Ag/AgCl inks	Flexible printed electrochemical sensing platform	170
Screen printing	Glucose, lactate	Paper	Carbon, silver inks, Ti_3C_2Tx/MB	Low-cost integrated sensing paper for sweat analysis	171
Screen printing	Na^+, K^+, glucose, lactate, pH	Stretchable substrate	Elastomeric or silver inks	Stretchable sweat-sensing platform with integrated battery and display	172
Screen printing	Uric acid, tyrosine, ascorbic acid	Polyimide (PI)	Cu, Au, Ag/AgCl ink	Wearable sweat sensor with laser-induced graphene electrodes	173
Screen printing	Glucose, lactate, Na^+, K^+, Cl^-, pH	PET	Carbon, Ag/AgCl	Highly integrated sensing paper (HIS) for real-time sweat analysis	171

Inkjet printing	Glucose	Tattoo paper	Prussian blue, glucose oxidase, chitosan	Wearable tattoo-based biosensor for glucose monitoring	174
Screen printing	Cd^{2+}, Pb^{2+}, uric acid, estradiol	Microbial nanocellulose (MNC)	Carbon paste	Microbial nanocellulose as a substrate for wearable electrochemical sensors to detect various analytes in sweat.	175
3D printing	Cortisol	Nanoporous flexible polyamide membrane	Palladium, MoS_2 nanosheets	Non-faradaic label-free cortisol biosensor using MoS_2 nanosheets integrated into a nanoporous flexible electrode system.	176
Screen printing	Cortisol	Flexible nanoporous polyamide substrate	Gold	Four-channel electrical impedance spectroscopy (EIS) module for cortisol biosensing in sweat.	177
Screen printing	Cortisol	Paper (Whatman No. 1 filter paper)	Polydimethylsiloxane (PDMS)	Portable 3D microfluidic origami biosensor for cortisol detection in human sweat.	178
Inkjet printing, screen printing	Sweat rate, conductivity, copper ions	Polyethylene terephthalate (PET)	Silver nanoparticles (AgNPs), carbon, Ag/AgCl inks	Fully printed wearable microfluidic nanosensor for sweat rate, conductivity, and copper detection.	179
Screen printing	Lactate	MgO-templated carbon (MgOC)	Poly (ethylene glycol) diglycidyl ether (PEGDGE), 1,2-naphthoquinone (1,2-NQ), lactate oxidase (LOx)	Continuous sweat lactate monitoring system with integrated screen-printed MgO-templated carbon-lactate oxidase biosensor and microfluidic sweat collector.	180
Screen printing	Urea	Polyethylene terephthalate (PET)	Polyaniline (PANI) ink, urease bioink, polyvinylchloride (PVC) membrane	Wearable potentiometric biosensor for on-body and on-site monitoring of urea in sweat.	181

Screen printing	Urea, ammonium	Polyethylene terephthalate (PET)	Carbon, silver/silver chloride (Ag/AgCl) inks	Touch-based potentiometric sensors for simultaneous detection of urea and ammonium from fingertip sweat.	182
-	Cortisol	-	-	Wearable and implantable cortisol-sensing electronics for stress monitoring.	183
Screen printing Inkjet printing, 3D printing, Aerosol Jet, Printing	Urea, glucose, lactate, electrolytes	-	-	Wearable organic electrochemical transistor patch for multiplexed sensing of calcium and ammonium ions from human perspiration.	184
Screen printing, Inkjet printing, 3D printing	Zn, Cd, Pb, Cu, Hg	-	-	Wearable sensors: modalities, challenges, and prospects.	1
-	Na^+, K^+	-	-	A thread/fabric-based band as a flexible and wearable microfluidic device for sweat sensing and monitoring.	185
-	Glucose, lactate	-	-	Flexible textile-based sweat sensors for wearable applications.	186
Screen printing	Sweat rate and electrolyte concentration	-	-	An unconventional vertical fluidic-controlled wearable platform for synchronously detecting sweat rate and electrolyte concentration.	187
-	Glucose	Flexible materials	-	Graphene-interfaced flexible and stretchable micro-Nano electrodes: From fabrication to sweat glucose detection.	188

Screen printing	Cortisol	Paper	-	A portable 3D microfluidic origami biosensor for cortisol detection in human sweat.	*178*

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The implementation of the R2R printing method for microfluidic chip fabrication and its use in sweat analysis was reported by Javey et al. [104]. The authors modified the PET substrate surface by forming silver and carbon electrodes via R2R printing. It should be noted that before printing, the PET surface was heated to 140 ºC to enhance substrate compatibility. After printing, the electrodes were cured in an oven. The fabricated microfluidic wearable paths were used for sweat analysis, specifically to determine [Na^+], [K^+], glucose concentrations, and sweat rate in both exercise and chemically induced sweat conditions. Whilst the R2R printing method has been widely adopted for stretchable and flexible wearable electronic devices, its use in sweat analysis is rare. A recent study demonstrated the applicability of the R2R screen-printing method for sweat-sensing devices [189]. The authors developed R2R screen-printed single-use sweat-sensing devices with high reusability and a robust interface, and the performance of the sensing systems was elucidated under both environmental heating and exercise conditions. To minimize sample (sweat) loss during transport from the sweat collector to the detection area, a microfluidic adhesive tape was implemented. The developed device designs are shown in Figure 10. While the sensors showed excellent promise for real-time monitoring of sweat rate, the small sensor capacity hinders the use of those microfluidic devices for more than 42 active minutes. Design limitations, such as motion artifacts, limit the design's sample capacity.

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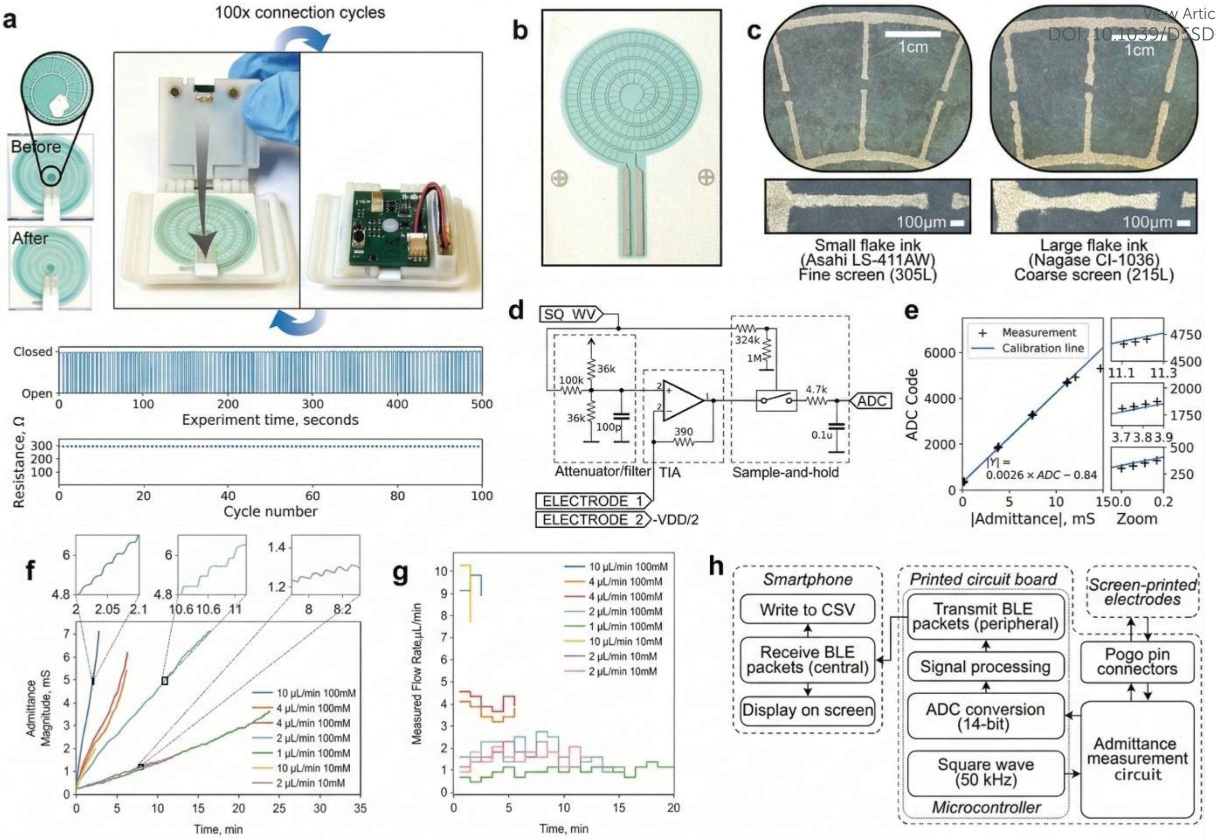

Figure 10. The design and testing of a new integrated circuit for measurements. (a)The first step involved testing the durability of the connection between the PCB and electrodes, which was achieved with spring-loaded pins and magnets; over 100 cycles, there was no significant increase in either contact or electrode resistance. (b)The electrode was fabricated by silk-screen printing silver ink onto a TPU 2D substrate (c), with LS-411 AW ink producing sharper patterns due to a finer mesh screen. (d)The core of the system is an admittance measurement circuit that includes a configurable excitation signal, a transimpedance amplifier, and a sample-and-hold detector, with its output being a voltage read by a microcontroller's ADC. (e) This channel was calibrated using discrete resistors. (f) and (g) raw admittance signal obtained from benchtop calibrations. (h) A block diagram illustrates the complete measurement system used for all admittance measurements, with permission from [189].

One of the most widely used printing technologies for developing wearable sweat sensors is screen printing. As shown in Table 3, various functional materials, including carbon, silver NPs, Ag/AgCl, Cu, Au, PDMS, PANI, and TMDs, were printed onto different substrates (PDMS, PET, PI, paper, cloth, PVC paper, carbon template, etc.). Yang et al. [166], For instance, prepared screen-printed, flexible, and wearable sweat sensors to measure Na^+ and K^+ ions in human sweat. The sensors consisted of six layers: a PET substrate, Ag/AgCl, carbon, PEDOT: PSS, and ISM. While the PET, Ag/AgCl, and carbon layers were implemented to facilitate signal conduction, the PEDOT: PSS layer served as the transducer in the sensor design. The

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sensor surface was then covered with an insulating layer formed by screen-printing insulating material and UV curing. The performance of independently prepared sensors was evaluated, yielding RSD% values of 9.73% and 8.86%, indicating acceptable deviation. The sensors displayed 55.731 and 54.480 mV/decade slopes between 1-32 mM K^+ and 5-160 mM Na^+ concentrations, respectively. In another study, Vinoth et al. [190] designed a microfluidic sweat-sensing device with low-dimensional sensing components via screen printing. The sampling efficiency was also enhanced by enhancing the hydrophobicity of the microfluidic channels. The microfluidic channels were prepared by the screen-printing of polystyrene-block-polybutadiene-block-polystyrene (SBS, styrene 30 wt% %) binder-based screen-printable carbon inks. The silver reference and carbon-based working electrode patterns were printed on flexible PI films (50 µm). It is essential to note that the authors devoted significant effort to developing printable silver and carbon inks with the desired viscosity and physical properties to meet the requirements of the screen-printing method. The performance of the wearable sensors was assessed against lactate, Na^+, K^+, and pH levels. The analytical responses of the ion-selective sensors were evaluated in vitro, and sensitivities of 9.5 and 60.1 mV decade^{-1} were obtained in the linear ranges of 0.02–200 mM and 0.01–100 mM for Na-ISE and K-ISE, respectively. The developed wearable sensors were also employed in pH sensing, and the pH values could be measured within the 3-8 pH window with a sensitivity of 71.4 mV/pH. Besides carbon-based materials, metal nanoparticles (Au, Cu, Ag, Pd, etc.) have also been used in the screen-printing method to develop wearable sensors, as reported by Chen et al.[173], wearable sweat sensors with high analytical performance and mechanical stability were developed by screen-printing Cu and Au layers to form the conductive pathway and prevent electronic resistance, respectively. Apart from the above-mentioned wearable sensors, the authors included laser-induced graphene formation technology to enhance sensor performance by increasing the physical surface area. The sensor's performance was tested for uric acid (UA), tyrosine (Tyr), and ascorbic acid (AA), demonstrating high sensitivity. Bimetallic compositions were also implemented in screen printing technology. Two-dimensional (2D) materials offer significant advantages for printing technology due to their tailorable surface properties, excellent electron transport, and large physical surface area. On the other hand, the restacking issue in layered 2D materials, driven by Van der Waals (vdW) forces between layers and by hydrophobic surfaces, should be carefully addressed to achieve inks with high homogeneity, stability, and printability. The discovery of graphene revolutionized 2D material research, and it has been one of the most widely used 2D materials in printing technology.

Graphene-based materials have been used in screen printing in various forms: graphene oxide, reduced graphene oxide, and pristine graphene.

While a vast range of conductive or non-conductive materials can be used as functional material in the ink composition, the printing parameters play a crucial role in achieving high-quality printed patterns. Therefore, the key printing parameters, including deposition height, contact angle, pseudoplasticity, filament size, pressure applied during the printing process, mesh geometry, interaction of the ink with the substrate, ink's cohesive and adhesive forces, material loading, viscosity of the ink, viscosity recovery time, and yield stress are essential parameters to achieve high print resolution and quality [191]. Therefore, in general, inks contain organic binders and rheological property modifiers, in addition to the functional material and the solvent—for example, as reported by Sen et al. [192] prepared flexible sensors by screen printing of MWCNT on acetate paper. The inks were prepared by mixing MWCNT, acrylic varnish, hardener, and liquid paraffin. Li et al. [171] investigated the electroanalytical performance of a printed sensing paper for direct analysis of sweat. The authors emphasized the importance of sweat collection, the use of wearable sensors for long-term study, and skin comfort.

Within this purpose, the researchers developed a cost-effective, disposable sensing paper (HIS) for sweat analysis. In the given sensor design, MXene/methylene blue ($Ti_3C_2T_x$/MB) hybrids were incorporated as active material. On the other hand, it should be noted that while the electrodes were fabricated by screen-printing of silver and carbon pastes, the $Ti_3C_2T_x$/MB functional material was drop-cast onto the working electrode surface. Thereafter, the working electrodes were modified with biological components to detect glucose and lactate levels. Bandodkar et al. [174] developed a fully printed tattoo-based iontophoretic biosensor with a different electrode pattern by screen printing. The in vitro performance of the tattoo sensor showed a linear response over 0-100 µM glucose, with a sensitivity of 23 nA/µM and a limit of detection of 3 µM.

Li et al. [165] documented a sweat collector based on graphene-patterned-array wearable devices. This work discussed the device's capability to collect and quantify sweat droplets. The electrochemical function of the device was demonstrated by H_2O_2 detection, with a limit of detection of 6 µM. Shitanda et al. [180] developed an online continuous lactate sensor system with an in-built screen-printed MgO-templated carbon-lactate oxidase biosensor. The system was determined to have a lactate detection limit of 0.3 mM and a dynamic range of 50 mM. The most common printing method is screen printing, which is used in most of the listed studies in Table 3. It is so popular because it has the ability to print functional inks of different types on

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various substrates, such as flexible and stretchable materials. This ability makes it a strong contender for wearables—for instance, Yang et al. [166] employed screen printing to fabricate a sweat sensor on polyethylene terephthalate (PET) for hydration status monitoring by measuring K+ and Na+ ions. Similarly, Li et al. [171] employed screen printing to create a highly integrated sensing paper (HIS) on PET for real-time multi-sweat analyte analysis (glucose, lactate, and electrolytes).

The choice of substrate materials also varies significantly, with PET, PDMS, and paper being commonly used. For example, Bandodkar et al. [174] developed a tattoo-based glucose sensor on tattoo paper via inkjet printing, demonstrating the potential for discreet, non-invasive monitoring. On the other hand, Kinnamon et al. [176] used a 3D-printed, nonporous, flexible polyamide membrane for cortisol detection, highlighting the use of advanced manufacturing techniques to enhance sensor performance.

The performance of sweat sensors is evaluated using metrics such as sensitivity, linear range, and limit of detection (LOD). These metrics provide insights into the sensor's ability to accurately and precisely measure the target analyte. For instance, the glucose sensor developed by Li et al. [171] exhibited a linear range of 0.08-1.25 mM with a LOD of 17.05 μM, demonstrating its capability to detect glucose at physiologically relevant concentrations. Similarly, the lactate sensor by Shitanda et al. [180] achieved a LOD of 0.3 mM and a dynamic range of up to 50 mM, making it suitable for monitoring lactate levels during exercise.

This table shows emerging trends in sweat-sensing technologies, such as the use of laser scribing to create patterned graphene arrays for sweat capture and the integration of microfluidics for continuous sweat monitoring. Furthermore, the development of wearable and implantable cortisol-sensing electronics and organic electrochemical transistor patches for multiplexed sensing, which point towards the future of personalized health monitoring, is well established in the literature.

5. Analytical Performance Metrics in Sweat Sensing

The analytical performance of wearable sweat sensors is typically evaluated on sensitivity, selectivity, stability, and response time. Among these, device sensitivity is the most important given the often-low concentrations of sweat biomarkers. Many printed electrochemical sensors now achieve sensitivities comparable to those of benchtop sensors. For example, a recently reported textile-based printed enzymatic sensor for metabolites showed high glucose sensitivity of 18.4 $\mu A \cdot mM^{-1} \cdot cm^{-2}$ with a linear range of 20–1000 μM [193], which is sufficient to detect low (tens to hundreds of μM) glucose levels in sweat. Leveraging novel advanced nanomaterials and ink formulations (e.g., MXene or NiO-modified inks) further improved sensor sensitivity.

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For example, a recently reported lactate sensor demonstrated sensitivities up to hundreds of $\mu A \cdot mM^{-1} \cdot cm^{-2}$ in vitro, which is an advancement for intense exercise monitoring [194].

The following analytical metric to be monitored in such sensors is selectivity. The target analytes must be measured without encountering interference from the sweat's complex matrix. Printed sensors employ ion-selective membranes, enzyme specificity, or molecularly imprinted polymers (MIPs) to achieve high selectivity. For example, a printed chloride sensor was reported to show no significant response to other sweat ions [169]. Similarly, the screen-printed textile glucose sensor noted above used a Nafion diffusion barrier to block interfering substances [193]. For cortisol, which is present at nM levels in sweat, published wearable sensors used MIP-based recognition. In one such flexible printed cortisol, the authors showed high specificity for cortisol, with negligible response to structurally similar hormones [195]. Thus, it is indeed clear that printed sensors can be engineered for excellent specificity, even ones comparable to lab assays.

Stability and reproducibility are also parameters that need to be monitored for practical wearables. Printed sweat sensors have shown encouraging stability both in storage and during operation. The printed textile glucose sensor reference above retained ~100% of its response after 30 days of storage, which demonstrates excellent shelf-stability1. Mechanical durability is also important, as such wearables undergo bending and exposure to sweat. Recent reports indicate that printed electrodes on flexible substrates indeed withstand repeated flexing without performance loss [196].

When the sensing element is functionalized with biological recognition elements (e.g., enzymes), many designs include protective coatings (e.g., epoxies or hydrogels) to prevent enzyme leaching or ink degradation and extend sensor operational stability. In terms of signal stability, printed ion-selective electrodes (ISEs) can maintain stable potentials for hours of continuous use if properly calibrated and a stable reference electrode is integrated [169]. Reproducibility between devices is generally high in these sensors due to the uniformity of the printing processes. For example, the printed ion sensors for Ca^{2+} and Cl^{-} were reported to exhibit minimal sensor-to-sensor variance and repeatable calibration curves across multiple devices [169].

Printed-on-skin sweat sensors can now be fabricated to display fast response times as well. The typical response time is on the order of seconds to several minutes, limited mainly by the transport of sweat samples rather than by intrinsic sensor kinetics. Electrochemical transducers (amperometric or potentiometric) respond almost instantaneously once sweat reaches the sensing interface. In practice, designs that minimize the required sample volume and improve

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sweat access yield the fastest responses. Notably, a recent breakthrough "meta-garment" with printed microfluidic fibers achieved a response time of only ~1.4 s and required just 0.1 µL of sweat – the fastest and smallest volume reported to date [197]. This is one example of a highly fast-response sensor; however, more commonly, printed sweat patches have response times on the order of tens of seconds as sweat wets the sensor. For example, a flexible pH sensor printed on a stretchable substrate reached steady-state readings in ~8 s [198]. Overall, leveraging thin and film-printed electrodes and efficient sweat collection enables modern devices to provide near-real-time monitoring of changing sweat chemistry.

6. Sensor Effectiveness for Common Sweat Biomarkers

Printed wearable sensors have been developed for a wide array of sweat biomarkers, with electrolytes and metabolites being the most commonly targeted. Analytes of interest include electrolyte ions (such as sodium (Na^+), potassium (K^+), chloride (Cl^-), and calcium (Ca^{2+}), metabolites (such as lactate, glucose, urea, and amino acids), and hormones or other markers (such as cortisol for stress or ethanol for alcohol monitoring). The effectiveness of printed sensors in detecting these targets has significantly improved in recent years, with many devices now capable of real-time, on-body measurements that correlate with physiological levels.

Electrolytes in sweat provide information on hydration status, electrolyte balance, and even disease diagnosis (for example, high sweat Cl^- is a marker for cystic fibrosis) [199]. Printed potentiometric sensors (ISEs) are the leading technology for detecting electrolytes. These typically consist of a screen-printed reference electrode (Ag/AgCl or solid-state) and a working electrode coated with an ion-selective membrane specific to the ion of interest. The printed ISE approach is highly effective; for example, sensors for Na^+ and K^+ often exhibit near-Nernstian sensitivity (~50–60 mV/decade concentration) and cover the whole physiological range of sweat (e.g., 10–100 mM Na^+, 5–50 mM K^+) [169].

A recent fully printed Na^+/K^+ patch demonstrated real-time tracking of electrolyte loss during exercise, with sensor readings closely matching expected changes in sweat composition [200]. For chloride, as noted earlier, a printed sensor yielded an ideal −59.5 mV/decade response and showed no cross-sensitivity to other anions [169]. As sweat contains a mix of ions (Na^+, K^+, Cl^-, typically in the tens of millimolar range, and others like Ca^{2+} or Mg^{2+} in the lower millimolar range), such devices must meet these sensitivity levels. By incorporating ion-specific membrane cocktails (e.g., valinomycin for K^+, selective ionophores for Na^+ and Cl^-), printed sensors effectively discriminate between ions. Many designs combine multiple ion sensors on one platform, such as when multiplexed printed patches can simultaneously measure Na^+, K^+,

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and Cl$^-$, or pH, providing comprehensive sweat electrolyte analysis [34,201,202] . The accuracy of these ion sensors in real sweat has been validated against standard analytical techniques. In one of the cited studies, for instance, a wearable Na$^+$/Cl$^-$ sensor patch was compared with ion chromatography of collected sweat. It showed deviations of only a few percent, confirming the sensors' quantitative reliability [169].

Printed wearable electrolyte sensors are highly effective, as they can provide continuous readings of ionic concentrations, support hydration monitoring, and even issue electrolyte imbalance warnings (as might be needed for athletes or workers in hot environments). Metabolic biomarkers in sweat, on the other hand, are indicators of physiological stress, exercise intensity, and metabolic health. Lactate in sweat, for example, correlates with muscle exertion and oxygenation, while glucose in sweat has been explored as a noninvasive proxy for blood glucose [165,166,171,174,190–192] . Printed enzymatic biosensors are commonly used for these targets. In such sensors, an enzyme (e.g., lactate oxidase or glucose oxidase) is immobilized on a printed electrode and selectively reacts with the target metabolite. The resulting product (often hydrogen peroxide) is then detected electrochemically. The effectiveness of printed lactate sensors has advanced tremendously, and they can now measure both resting and exercise-induced levels. Typical sweat lactate might range from ~1 mM at rest to >15 mM during intense exercise. A recent wearable lactate patch reported a linear range of 1–20 mM with sensitivity around 0.6 µA/mM (in a three-electrode configuration) [203]. This allows the user to track lactate build-up and clearance during workouts.

Glucose is a more challenging analyte due to its lower sweat concentration (often 100–200 µM, though highly variable). However, recently reported sensors, such as the textile-based sensor described earlier, had a detection range starting at 20 µM [193], which covers the upper end of typical sweat glucose levels. In on-skin tests, this sensor could clearly detect a rise in sweat glucose after the subject ingested a high-sugar meal. Although sweat glucose does not track blood glucose with as much precision as other targets, as it typically lags and is much lower in concentration, these sensors are effective for observing relative changes or screening for abnormal levels. They also tend to have high selectivity, as, for example, in the case of using a Prussian Blue mediator and a Nafion coating in the printed glucose sensor, which minimized interference from co-existing lactate or ascorbate [193]. Thus, it can be said that sweat glucose readings can be obtained reliably in real time, which represents a significant step toward noninvasive glucose monitoring.

Sweat sensors have successfully targeted other metabolites and small molecules. Cortisol, a stress hormone, is present in sweat in low nanomolar concentrations and has traditionally been measured via lab assays. Recent wearable designs have used printed electrodes functionalized with aptamers or MIPs for cortisol, demonstrating the ability to detect physiologically relevant fluctuations in cortisol levels. For example, a flexible cortisol patch with a printed CNT-MIP composite electrode detected a cortisol increase (~10–20 nM) in sweat within 15 minutes of a stress event (ice-water hand dip), followed by its return to baseline[195] . Such devices indicate that even hormones can be monitored by printed sweat sensors with reasonable sensitivity and time resolution.

Other biomarkers measured include sweat pH. Printable pH sensors are often made by screen-printing pH-sensitive polymer or oxide inks, which easily cover the normal sweat pH range of ~4.5–7.5 [184,203]. Urea and ammonia are indicators of metabolic waste and kidney function and can now be measured using printed colorimetric patches or amperometric enzymatic sensors [193–196,204]. Moreover, sweat sensor patches can also detect heavy metals or drugs. For example, sweat sensors on flexible substrates have been used to detect lead and cadmium in sweat for environmental exposure monitoring [197–199]. While these latter sensors are less common, their development demonstrates the broad applicability of printed sweat sensing. Virtually, at the time of this review, any analyte for which a selective chemistry can be devised (enzyme, ionophore, molecular receptor, etc.) can find a printable ink that can be deployed in a sweat sensor for said analyte. The effectiveness of detecting each biomarker ultimately depends on how well the pairing between the appropriate sensing mechanism and the most performant printed platform is done.

6. Application

The development of wearable electrochemical sweat sensors has opened a wide range of applications across diverse fields, from sport and fitness monitoring and disease control to industrial safety and health, to individualized healthcare. Such applications leverage sweat sensors' ability to trace, in real time and non-invasively, a variety of biomarkers, providing valuable insights into an individual's physiological status and enabling targeted interventions.

6.1 Sports and Fitness Monitoring

Wearable sweat sensors offer a powerful tool for athletes and fitness enthusiasts to monitor their hydration status, electrolyte balance, and metabolic markers during physical activity. By continuously tracking sweat composition, these sensors can provide real-time insights into an individual's physiological state, enabling informed decision-making and personalized training strategies [13,13,90,204].

Figure 11 shows a collection of innovative wearable biosensors designed for sweat analysis, offering a glimpse into the future of healthcare and disease monitoring. Examples of sensors

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integrated into patches, smart bands, and even ear-worn devices that aim to capture and analyze various biomarkers in sweat are shown in this figure. These examples highlight the diversity of sensing mechanisms, from enzymatic reactions for lactate detection to electrochemical sensing for electrolytes and metabolites. Additionally, it emphasizes the trend towards non-invasive, real-time health monitoring, with devices capable of wirelessly transmitting data to smartphones for convenient tracking and analysis. These advancements in wearable biosensor technology hold immense promise for personalized healthcare, fitness tracking, and early disease detection [205–209].

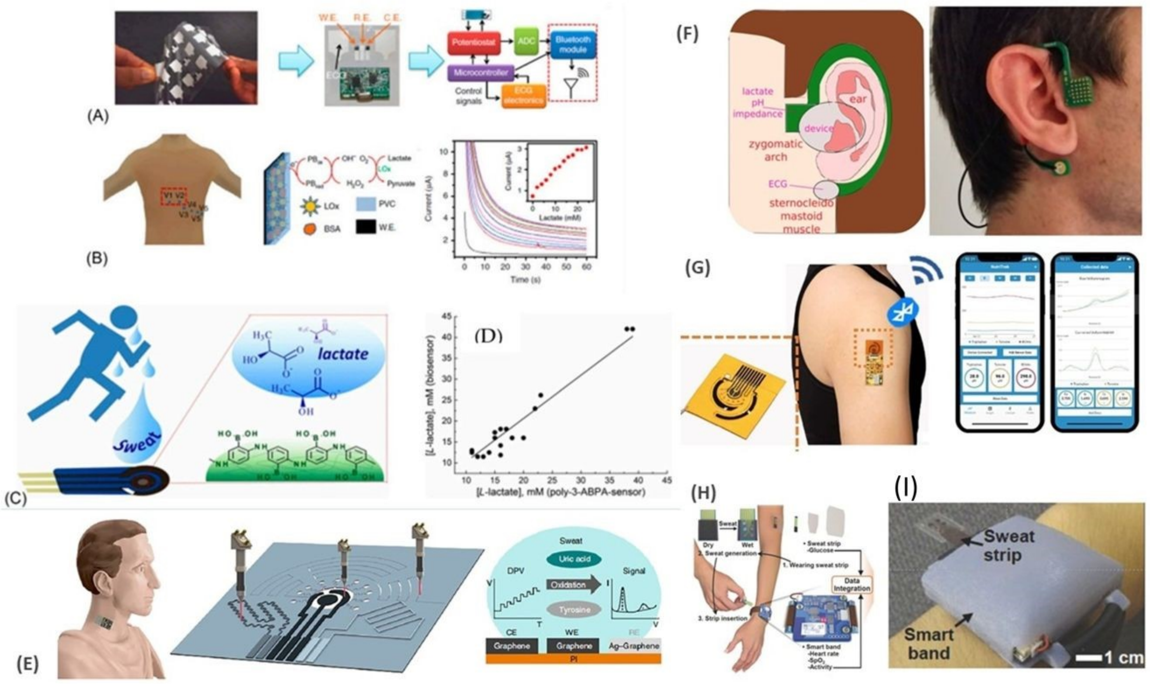

Figure 11. Device photographs of a sweat-based sensor on the body and its sensor features (A–B) with permission from Elsevier[205], schematic representations of screen-print, block diagram of the circuit, enzymatic sensing mechanism, and amperometric response of wearable sweat-based lactate biosensor (C) with permission from Elsevier[205], example of non-enzymatic lactate sensor in human sweat, and correlation diagram for lactate (D) with permission from Elsevier[205] A wearable laser-engraved sensor for the sensitive detection of uric acid and tyrosine in sweat (E) With permission from [206]. A wireless ear-worn device capable of pH, lactate, and ECG sensing during physical exercise (F) With permission from [207]. A wearable electrochemical biosensor for monitoring of multiple metabolites and nutrients (G) With permission from [208]. A wearable smart band for detecting sweat-based glucose and vital signs (H) With permission from [209].

Sodium, potassium, and chloride are electrolytes that serve essential functions in hydration and muscle function[210–212]. Sweat sensors can quantify levels of these electrolytes, allowing athletes to optimize their hydration practices and electrolyte replacement [213]. For. For example, Paolo et al. [16] developed a wearable sensor system that quantifies sodium and potassium ions in sweat during exercise. The researchers found that real-time feedback enabled players to maintain an ideal electrolyte balance, which is key to performance and recovery.

Lactate is a byproduct of anaerobic metabolism and a significant indicator of exercise and muscle fatigue [214–217]. Real-time lactate monitoring using sweat sensor-based technology can help athletes track their intensity levels, prevent overtraining, and adjust their training regimens accordingly. Lee et al. [218] developed a flexible, wearable glucose biosensor that accurately measured glucose concentration in sweat during exercise. Scientists demonstrated that this sensor can provide rivals with valuable information on exercise intensity and the capability to adjust their training programs. Dehydration also significantly impacts an athlete's performance and recovery. Sweat sensors can monitor biomarkers of hydration, including sodium, potassium, and chloride concentrations in sweat, as well as sweat flow rate and fluid intake. By providing instant feedback regarding hydration levels, such sensors will help athletes ensure they are optimally hydrated and prevent complications associated with dehydration [218,219].

6.2 Disease Management

Wearable electrochemical sweat sensors have the potential to revolutionize disease management by enabling continuous and non-invasive monitoring of biomarkers associated with various conditions. Sweat sensors have been developed to detect glucose levels, offering a promising alternative to traditional blood glucose monitoring for individuals with diabetes [220,220,221]. Continuous glucose monitoring via sweat can provide better insights into glucose fluctuations, enabling more effective disease management. For instance, Xuan et al.[222] developed a flexible, wearable electrochemical sensor that accurately monitors glucose levels in sweat. This technology could potentially eliminate the need for frequent finger-prick blood tests, improving patient compliance and quality of life. Figure 11.b. demonstrates the schematic of an enzymatic biosensor to detect glucose in sweat[204].

Cystic fibrosis is a genetic disorder characterized by abnormally high chloride ion levels in sweat. Sweat sensors can be designed to detect chloride ion concentrations, enabling better management and treatment of this condition [223,224]. Coyle et al.[225] developed a wearable sweat sensor capable of measuring chloride levels in real time, which could be used to monitor cystic fibrosis patients and adjust their treatment accordingly. Specific biomarkers in sweat, such as creatinine and urea, can provide insights into kidney function [226]. Wearable sweat sensors can continuously monitor these biomarkers, enabling early detection of kidney disorders and facilitating timely interventions. Alizadeh et al. [41] developed a flexible, wearable sensor for monitoring creatinine levels in sweat, demonstrating its potential for noninvasive kidney function monitoring.

Sweat sensors can also be used to monitor biomarkers associated with metabolic diseases, such as diabetes and obesity [227,228]. For example, Karpova et al. [229] developed a wearable sensor to monitor metabolites, such as glucose and lactate, in sweat, providing valuable insights into metabolic processes and aiding in the management of metabolic disorders. Specific biomarkers in sweat, such as cytokines and other inflammatory markers, can indicate the presence of inflammatory conditions. Wearable sweat sensors can monitor these biomarkers, enabling early detection and personalized treatment strategies for conditions like rheumatoid arthritis, inflammatory bowel disease, and other autoimmune disorders [33,229].

6.3 Occupational Health and Safety

In industrial and occupational settings, wearable sweat sensors can play a crucial role in monitoring worker health and safety. Sweat sensors can detect the presence of toxic substances or environmental pollutants, alerting workers to potential exposure and enabling timely intervention [179,230]. For example, Gao et al.[231] developed a wearable sensor that could detect heavy metal ions, such as lead and cadmium, in sweat. This technology could be valuable in industries where workers are at risk of exposure to toxic substances, such as mining, manufacturing, and construction. Certain chemicals and volatile organic compounds (VOCs) can be excreted through sweat, and their presence can indicate exposure to potentially harmful substances. Wearable sweat sensors can detect these chemicals, enabling monitoring and early intervention for workers in industries where chemical exposure is a risk, such as manufacturing, agriculture, and chemical processing [24,232]. Sweat sensors can monitor physiological markers of heat stress, dehydration, and fatigue, which are critical considerations in physically demanding or extreme environments [233,234]. By providing real-time feedback, these sensors can help prevent heat-related illnesses, improve worker productivity, and enhance overall safety conditions. Sonner et al. developed a wearable sweat sensor that could monitor electrolyte levels and sweat rate, enabling early detection of heat stress and dehydration in workers exposed to high temperatures or physically demanding tasks.

6.4 Personalized Healthcare

The integration of wearable electrochemical sweat sensors into personalized healthcare systems holds immense promise. By continuously monitoring an individual's sweat composition, these sensors can provide a comprehensive picture of their physiological state, enabling proactive and personalized healthcare interventions. Sweat sensors can be used to monitor medication adherence and therapeutic drug levels, ensuring optimal dosing and treatment efficacy [235–237]. For example, Emaminejad et al. [67] developed a wearable sensor that could detect specific drugs in sweat, enabling monitoring of medication adherence and adjusting dosages accordingly.

7. Challenges and Outlook

The field of printed wearable sweat sensors has seen notable breakthroughs in the past few years (2022–2025) [238–242], even as specific challenges remain focal points of research. Improved materials design, innovative device architectures, and system-level integration are all contributing to these advances and to the high analytical performance of wearable sweat sensors. One significant advance in recent years is in multi-analyte sensing and system integration. Early sweat sensors typically measured a single biomarker, but recent devices can detect a panel of biomarkers simultaneously. For example, researchers demonstrated a fully integrated "smart wristband" that incorporated multiple printed sensors (for Na^+, K^+, and lactate) along with a microcontroller and a Bluetooth module on a flexible printed circuit, essentially representing a lab-on-a-watch for sweat analysis [190]. In 2025, a "meta-garment" for firefighters was reported, requiring only 0.1 µL of sweat and 1.4 s to obtain readings [197].

Nanostructured materials such as MXene, conductive polymers, and nanoparticle composites have been formulated into printable inks to improve sensitivity and stability [116,218,223–226,228]. For example, incorporating carbon nanotubes or graphene into the ink can increase electrode surface area and electron transfer, yielding higher currents for a given analyte concentration [195]. Enzyme immobilization techniques were also improved by using polymer matrices or crosslinkers printed alongside the enzyme to prolong its activity. There have also been enzyme-free sensor developments, such as an MXene/Ni–LDH–based glucose sensor that achieves low detection limits via catalytic electrooxidation of glucose[168]. These improvements often lead to better sensor stability and broader operating conditions. From a fabrication standpoint, 3D printing is emerging as a complementary approach for creating structural components of wearable sensors. One such example is 3D-printed microfluidic networks or scaffoldings that hold the printed electrodes in contact with the skin.

Despite these advances, several challenges remain to be addressed to achieve ideal printed sweat sensor designs. One challenge is the long-term stability during continuous wear. While sensors can last days, requirements for truly continuous health monitoring might demand weeks or months of operation without maintenance. This raises issues such as biofouling (skin debris accumulating on sensors) and long-term drift. Researchers are investigating antifouling coatings and on-the-fly calibration schemes to counter this [33,228]. Another challenge is calibrating and standardizing sweat readings. Sweat composition can be influenced by sweat rate, and therefore, the same sensor reading might mean different things under different conditions. To address this, some wearable devices now include sweat rate sensors, such as printed microfluidic channels that measure sweat volume alongside chemical sensors, enabling normalization for dilution effects [243,244]. Additionally, more work is needed to correlate sweat analyte levels with blood levels for specific biomarkers, such as glucose or cortisol. Extensive clinical studies are underway to correlate those relationships, which will inform the calibration models used in devices. Interference and cross-reactions pose additional challenges, especially in multiplexed devices. These challenges show there is still a need for improvements in system design when combining functionalities. Although printed sensors themselves require little power, another challenge is that wireless transmission and data logging do. Here, an exciting development is self-powered sweat sensors that harvest energy from the body or the environment. For example, biofuel cells that generate power from lactate in sweat, or flexible solar cells, can be used in such sensors [245,246].

Another critical challenge arises when scaling up the fabrication process, as it is associated with maintaining the performance and reproducibility of both the fabrication process and the analytical response. It should be emphasized that analytical response repeatability is a key requirement for clinical applications. While the printing methods discussed in the given review are ready for scale-up operations, additional parameters should be considered when (bio)sensing technology is the intended application.

A SWOT (strengths, weaknesses, opportunities, and threats) analysis was performed to clearly demonstrate the strengths and weaknesses of the printed sensors (Figure 12). High analytical performance, non-invasive and low-volume sensing capability, and a scalable fabrication process are among the strengths of printed sweat sensors. In addition, those sensors can be integrated into different systems, enabling the development of fully integrated sensing platforms. Therefore, the printed sensors demonstrate the strong potential in electrochemical sweat analysis in health, safety, and sports applications. On the other hand, some challenges, including limited long-term stability, interference, and cross-reaction problems, should be alleviated for real-world applications. In addition, to minimize false readings, the sensor response should be calibrated against fluctuations that happen in samples (sweat rate, changes

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in sweat composition depending on body condition) and across experiments. The current literature indicates insufficient storage time (e.g., days or weeks) and should be extended to months. Addressing the mentioned weaknesses in printed sweat-sensing systems will create significant opportunities in personalized healthcare, continuous and real-time biomarker monitoring, and the use of a non-invasive method. In addition, the design of self-powered analysis platforms will enable the development of battery-free wearable sensors. It should be noted that to have commercialized printed sweat sensors, several treats should be addressed, such as the approval of those systems for clinical applications, and validated and standardized results are crucial. Moreover, scalable, reproducible sensing platforms with uniform responses should be developed.

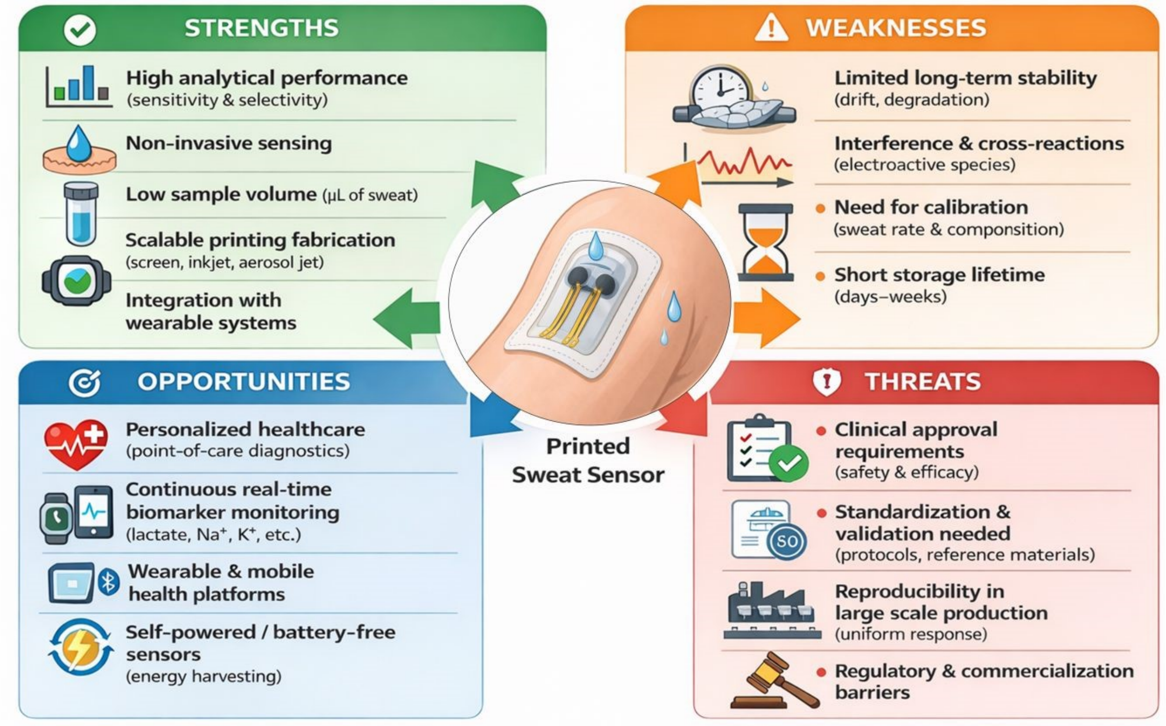

Figure 12. SWOT analysis for printed sweat sensors.

8. Conclusion

The development of printing methods and their application in fabricating low-cost, flexible electrodes has opened a new path in electrochemical sensors, especially for sweat analysis. Printed wearable sensors offer a transformative approach, especially in healthcare, by enabling noninvasive, continuous monitoring of biomarkers in sweat. As discussed, the implementation of versatile printing methods, including screen printing, inkjet printing, 3D printing, and aerosol jet printing, has revolutionized the fabrication of customized, flexible, and low-cost sweat sensors. Besides the fabrication methods, the development of new materials, including MXenes, carbon nanotubes, conductive polymers, metal nanoparticles, and graphene, with a wide range of electrochemical properties, has enabled the development of high-performance sweat sensors with low limits of detection and selectivity. The integration of sweat sensors with microfluidics, microcontrollers, and wireless or Bluetooth communication modules accelerated the development of sweat-sensing technology. While printed sweat sensors are important for future sensing technology, several challenges should be addressed, including insufficient sensor stability, issues with sweat collection and sampling, and nonuniform analytical response. The stability of the sweat sensors should be extended to weeks and even months for continuous monitoring. The variation in sensor response associated with fabrication and the analytical response reproducibility should be less than 10% RSD. Moreover, drifts in sensor performance and sensor voltage noise should be minimized. Non-enzymatic detection routes are considered a promising approach to enhance storage stability. Mitigating those technical challenges will make printed sensors indispensable, especially in sports physiology and the diagnosis of chronic diseases. For practical deployment, printed sweat sensors should be evaluated against several quantitative benchmarks. Recent reports indicate that excellent storage stability can reach ~100% signal retention after 30 days, while future wearable platforms should target stability over weeks to months[166,247–249]. For rapid and low-volume operation, state-of-the-art microfluidic systems have demonstrated response times of ~1.4 s with only 0.1 µL of sweat. In terms of reproducibility, device-to-device variation should ideally remain below 10% relative standard deviation (RSD), as independently prepared screen-printed sensors have shown RSD values of 9.73% and 8.86% [166,250,251].

Appendix

2D: two-dimensional
3D: three-dimensional
Ag NP: Silver nanoparticle
AJP: aerosol jet printing
CNT: carbon nanotube
DIW: direct ink writing
DLP: digital light processing
EHD: electrohydrodynamic
FDM: fused deposition modeling
ISEs: ion-selective electrodes
LCR: inductance, capacitance, resistance
LDH: layered double hydroxide
LIBT: laser-induced backward transfer

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LIFT: laser-induced forward transfer
LOD: limit of detection
MgOC: MgO-templated carbon
MIP: molecularly imprinted sensor
MNC: microbial nanocellulose
MXene: two-dimensional transition metal carbide/nitride
PANI: polianilin
PBS: phosphate-buffered saline
PDMS: polydimethylsiloxane
PEDOT: PSS: poly(3,4-ethylenedioxythiophene) polystyrene sulfonate
PEN: polyethylene naphthalate
PET: polyethylene terephthalate
PI: polyimide
PVC: polyvinyl chloride
R2R: roll to roll
SLA: stereolithography
SPCE: screen-printed carbon electrode
SWOT: strengths, weaknesses, opportunities, and threats
TPU: thermoplastic polyurethane
UV: ultraviolet
VOC: volatile organic compounds
WMFSH: wearable microfluidic fresh sweat harvesting

Acknowledgement

A.U. Acknowledge the financial support of TUBITAK for the project: 122N920.

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DOI: 10.1039/D5SD00221D

Data Availability Statement:

No primary research results, software or code have been included and no new data were generated or analysed as part of this review.