

Review Article

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Recent advances of sweat sampling, sensing, energy-harvesting and data-display toward flexible sweat electronics

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Abstract

Sweat contains diverse types of biomarkers that can mirror an individual's health condition. The forefront research of sweat monitoring primarily focuses on sensing basic parameters, i.e., sweat rate and single electrolyte imbalances in controlled laboratory settings. However, recent works show the potential of sweat for the rich biomarkers in aspects of comprehensive health status display, timely safety alarming, and energy harvesting. The advances in wearable flexible electronics enable continuous, real-time, noninvasive detection of multiple sweat components, providing molecular-level insights into human physiology and psychology information; additionally, the efficient sweat extraction technologies of flexible electronics promote its application in energy harvesting, contributing to advancing a flexible sweat platform. This review comprehensively explores flexible sweat-based electronics, encompassing four key aspects: sweat sampling methods, sweat-based sensors, sweat-based energy harvesters, and sweat data display methods. Firstly, the traditional sweat-based platform is discussed in sweat sampling, sensing, and data analysis. Then, the development of wearable sweat sampling methods is discussed with a comparison of the traditional sweat collection methods. After that, the recent advances in sweat-based biosensors for monitoring diverse sweat analytes, such as the perspiration volume, glucose, lactate, and uric acid levels, are summarized. Subsequently, this review also highlights the recent progress and potential value of sweat-based energy harvesters in sweat-activated batteries and bio-fuel cells. Furthermore, multiple data display methods are proposed to achieve accurate feedback on health status, such as colorimetric techniques, light-emitting diodes, actuators, etc. Finally, this review concludes the main current challenges faced in practical



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applications of sweat-based bioelectronic systems and proposes a vision for the future evolution of this promising field.

Keywords: Sweat electronics, sweat sampling, sweat sensing, sweat-based energy harvester, data display

INTRODUCTION

Sweat, one of the most important body fluids, primarily consists of water (~99%)^[1]. It also comprises metabolites (such as glucose, lactate, ethanol, *etc.*), ions [including potassium ions (K^+), sodium ions (Na^+), ammonium ions (NH_4^+), chloride ions (Cl^-), *etc.*], hormones, small proteins and peptides, offering abundant biochemical information regarding human physiological and metabolic status^[2-9]. For example, the concentration of Cl^- is the benchmark for diagnosing cystic fibrosis; the level of Na^+ is a key indicator for athletes as it guides the fluid intake strategies and helps maintain the balance between hydration and electrolyte levels^[10-12]. Sweat glucose analysis has been employed to evaluate the glucose variation in blood for diabetes in clinical applications^[13-15]. Recently, sweat is also utilized in clinical pharmacokinetics studies to examine the variation of some xenobiotics, such as drug molecules^[16-18]. Among various biofluids, blood and interstitial fluid can be continuously monitored but are invasive and require additional processing^[19,20]. Saliva, although easily obtainable, presents limitations such as reduced flow during the day, non-uniform composition across different parts of the mouth, and susceptibility to contamination^[21]. Tear collection, on the other hand, is a little uncomfortable for participants and easily accessible. However, the quantity of tears collected is limited, and studies investigating their validity and reliability are scarce^[22,23]. Additionally, collecting sweat samples is generally less challenging than urine collection^[24]. Compared with other bodily fluids such as blood, interstitial fluid, urine, saliva, and tears, sweat holds significant promise due to the merits of safety, rapid processing, easy preparation, noninvasiveness, and so on^[20,25-27]. Therefore, achieving rapid and accurate monitoring of sweat serves a significant role in health management and medical diagnosis. However, clinical use of sweat is presently limited by high costs, complex sampling procedures, significant time and manpower consumption, and the requirement of large-scale medical equipment, among other factors^[28].

Advances in materials, biotechnology, and electronics have enabled flexible sweat electronics^[27,29-31]. These devices, with sweat sampling, biosensors, energy harvesters, and data displays, enable noninvasive and continuous physiological monitoring^[32-34]. They can harness energy from sweat using sweat-activated batteries (SABs) or supercapacitors (SACs)^[35-37]. Flexible sweat electronics offer real-time health updates and clinical treatment alerts, making them increasingly important in healthcare^[38-40].

Several works have been reported on the progress of sweat capture, collection, and sensing techniques^[11,13,26,35,41-43], comprehensively summarizing sweat sampling and sensing. This review explores various aspects of flexible sweat electronics, including sweat sampling, sensors, energy harvesters, and data display [Figure 1]. It compares traditional methods with flexible sweat electronics, covers advancements in sweat biosensors, and discusses sweat-based energy harvesters such as sweat-based fuel cells, SABs and SACs. The review also addresses data display methods and highlights scientific obstacles and future opportunities. Overall, the main goal of this article is to thoroughly overview flexible sweat electronics that will facilitate personal health management and finally cause a paradigm shift in medical care.

TRADITIONAL SWEAT-BASED PLATFORM

The sweat platform has made significant progress, with various methods used to collect sweat components. One typical traditional approach in the 1990s involved full body washing to assess overall sweat electrolyte

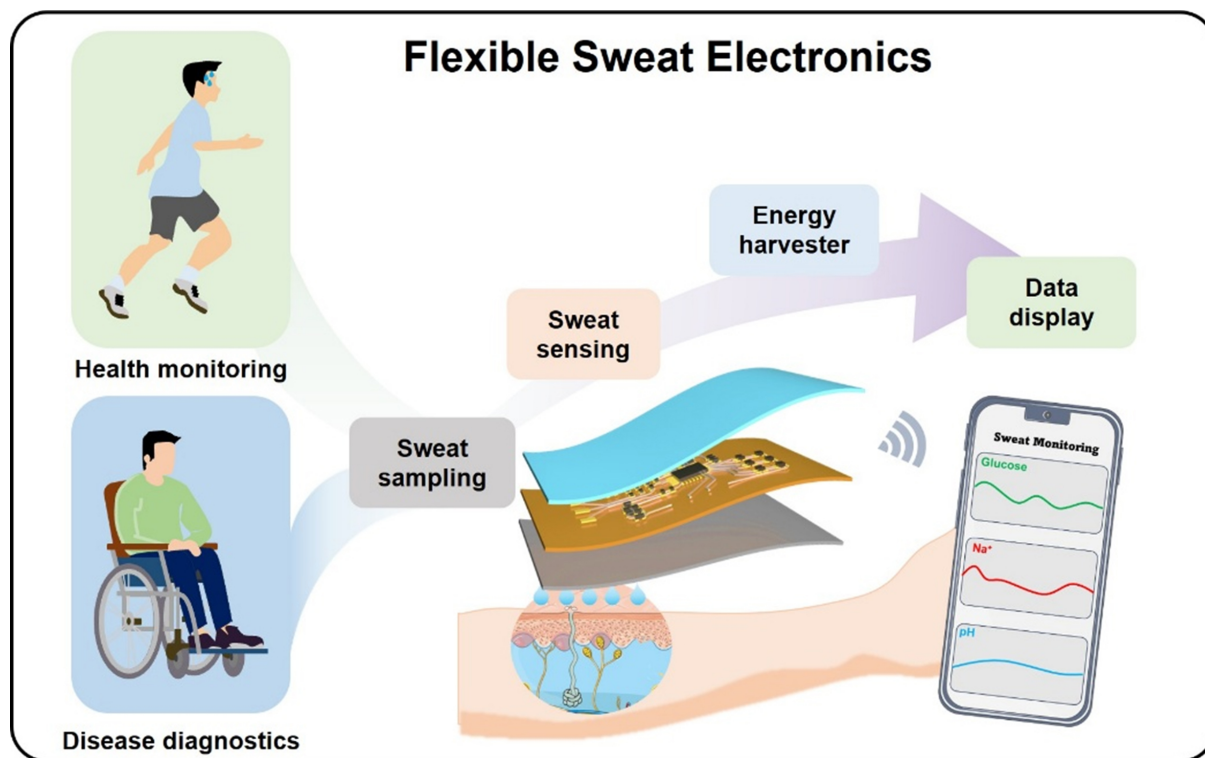


Figure 1. Schematic diagram of flexible sweat electronics.

loss. It avoids contamination and interference with natural sweating. During the study, participants engaged in exercise within a plastic isolation box on a cycle ergometer, dressed simply. After exercise, everything they touched was rinsed using deionized water to collect the electrolytes produced by their bodies. The difference in body mass before and after exercise was measured to determine the total sweat loss^[44]. Another sweat collection method involved gathering samples from patients' backs in a sauna. The process included cleaning the back with a moist towel, draping it with a hole and petroleum jelly, and collecting fluids in a pocket as individuals took a sauna bath. Sweat was then collected using a syringe and filtered through a cartridge-style filter [Figure 2A]^[45]. Absorbent patches were also introduced as an alternative to traditional collection methods. These patches efficiently absorbed sweat, allowing for local analysis through centrifugation. Subsequently, the sweat sample was tested using a laboratory device for Na⁺ and K⁺ detection [Figure 2B]^[46]. However, all these approaches are impractical for field research and treadmill protocols due to the controlled laboratory environment, complex processes, and other limitations^[47]. Recently, Brueck *et al.* have proposed a calorimetric-based flow-rate detection system for sweat detection [Figure 2C]. The whole system includes Macroduct for sweat sampling, a calorimetric sensor for sensing, a printed circuit board (PCB) for system control, and a rigid lithium battery for power, which is very bulky and lacks portability^[48].

Advancements in skin electronics have overcome challenges in previous sweat-based platforms, enabling real-time sampling, sensing, energy harvesting, and data display. This review will comprehensively explore the advancement of flexible sweat-based electronics and the progress achieved so far.

DEVELOPMENT OF FLEXIBLE SWEAT SAMPLING METHODS

Skin-electronics-based sweat sampling methods

Novel sweat collection methods for flexible electronics have been proposed to overcome limitations of

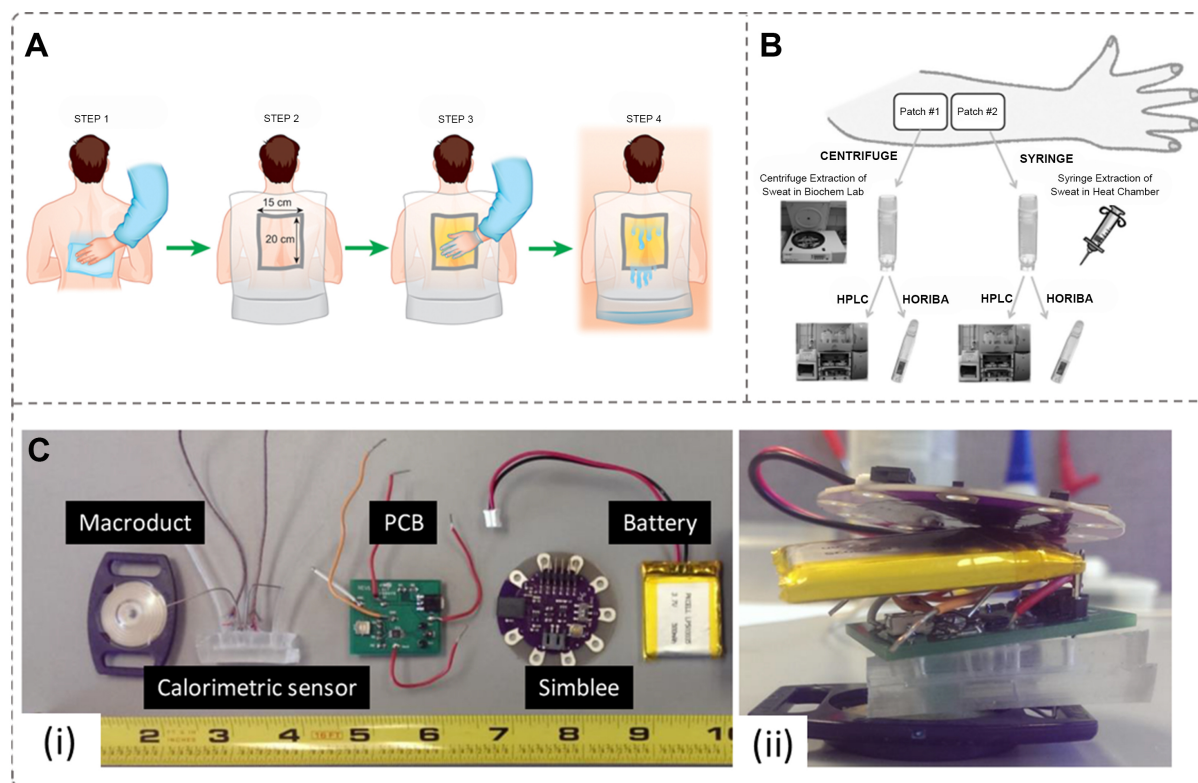


Figure 2. Traditional sweat-based platform. (A) Pocket-shape drape in sauna. Reproduced under the terms and conditions of the CC BY^[45]. Copyright 2018, Author(s), published by PLOS; (B) Sweat extraction patched for Na⁺ and K⁺ analysis. Reproduced under the terms and conditions of the CC BY^[46]. Copyright 2014, Author(s), published by Wiley-VCH; (C) Traditional sweat-based electronics in sweat sampling, sensing and data display method (i) and overall device view after the assembly (ii). Reproduced under the terms and conditions of the CC BY^[48]. Copyright 2018, Author(s), published by MDPI.

traditional methods. One low-cost material with strong water absorption properties is the sponge. Huang *et al.* introduced versatile soft substrates as a method for microfluidic sweat sampling, analysis, and display to integrated electronic sensors or external camera systems [Figure 3A]^[49]. These substrates enable the spontaneous collection of sweat using capillary forces, avoiding the necessity for intricate microfluidic manipulation setups. However, due to the open construction and porous substrate, the sweat absorbed by the sponge can easily vaporize, making it unsuitable for long-term assessment^[49]. Conventional fabrics can be modified to exhibit superhydrophobic or superhydrophilic properties, allowing for efficient droplet utilization, minimal microdroplet enrichment, and strong microdroplet anchoring. Dai *et al.* developed a hydrophobic/superhydrophilic textile with a conical micropore array [Figure 3B]^[50]. This textile allows directed liquid transport, pumping excess perspiration from the hydrophobic polyester (PE) to the superhydrophilic nitrocellulose (NC) layer. It enables accurate sweat collection, controls excessive sweat, and prevents discomfort. Conventional fabrics modified this way exhibit efficient droplet utilization and minimal microdroplet enrichment^[50]. In order to improve sweat absorption, textile (rayon) was harnessed to capture and convey perspiration from the skin to the upper hydrogels^[51]. Compared to textiles, filter paper is an affordable and highly absorbent material, making it an ideal wick layer for wearable surface lipid masks. Jain *et al.* introduced a colorimetric platform for measuring sweat volume by utilizing filter paper that could easily attach to the skin. The paper strip absorbs perspiration and carries dyes stored in a reservoir. The length of the stained paper is measured to calculate the sweat volume [Figure 3C]^[52]. Hydrogel is also a promising material for sweat sampling due to its higher swelling ratio^[53]. Sempionatto *et al.* proposed a touch-based sweat collection and electrochemical glucose detection method using polyvinyl alcohol (PVA)

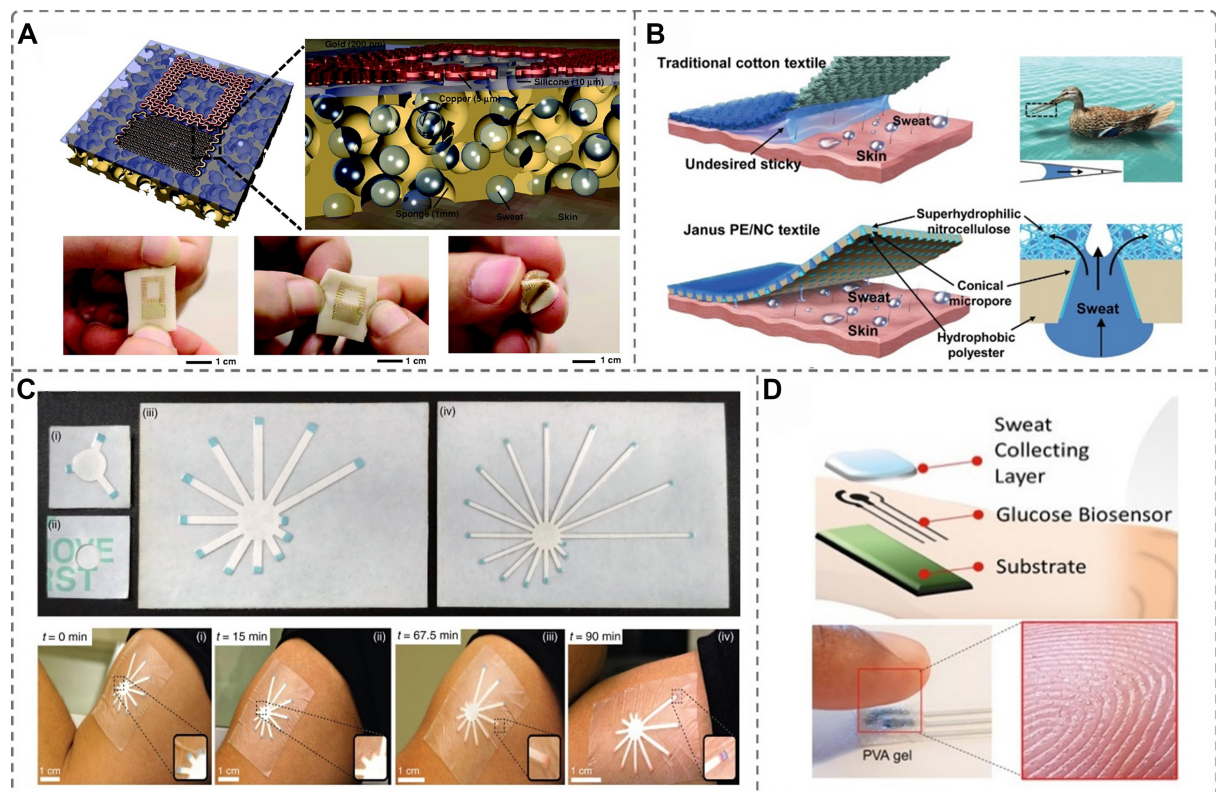


Figure 3. Material design for sweat sampling in flexible sweat electronics. (A) Sponge substrates for sweat collection. Reproduced with permission^[49]. Copyright 2014, Wiley-VCH; (B) Hydrophobic/superhydrophilic textile for directed sweat transportation. Reproduced with permission^[50]. Copyright 2019, Wiley-VCH; (C) Filter paper-based sweat volume colorimetric platform. Reproduced under the terms and conditions of the CC BY^[52]. Copyright 2019, Author(s), published by Springer Nature; (D) PVA Hydrogel for sweat absorption. Reproduced with permission^[54]. Copyright 2021, American Chemical Society. PVA: Polyvinyl alcohol.

gel as the hydrophilic material to absorb sweat on the fingertip. The touch sensor device is shown in [Figure 3D](#)^[54].

In addition to the absorbing way to collect and analyze sweat, sweat guidance is also a very important alternative for flexible sweat sensing, which leads to multiple kinds of research on the epidermal microfluidic systems. [Figure 4](#) displays wearable sweat sensor devices that gather, transfer, and hold onto perspiration inside the device using microfluidic technology. A sweatband fluidic platform [[Figure 4A](#)], can be worn comfortably on a person's forehead to collect sweat effectively and do wearable analysis during indoor cycling. With the help of gravity and movement oscillation, perspiration that appears on a subject's forehead might effectively flow into the channel and be carried to the chip surface^[55]. A novel three-dimensional (3D) printed epifluidic platform, referred to as a "sweatiner" [[Figure 4B](#)], comprises an adhesive gasket, polydimethylsiloxane (PDMS) reservoir capping layer, and a microfluidic network with sealed and unsealed reservoirs. The platform allows sweat to enter through the intake, flow through microfluidic channels, and be collected using capillary burst valves (CBVs). Integrated ventilation holes prevent backpressure and ensure smooth flow^[56]. Sweat loss from the microfluidic device outlet frequently causes a discrepancy between the actual and measured concentration of the electrolyte or biomarker. To address discrepancies caused by sweat evaporation, Zhang *et al.* developed a chamber with hydrophobic valves, allowing for reduced evaporation and contamination. The practical utility of these devices is demonstrated by real-time sweat loss measurements and pH analysis, with multiple chambers available for analyzing biomarkers such as chloride, pH, and glucose [[Figure 4C](#)]^[57]. Son *et al.* developed a patch with

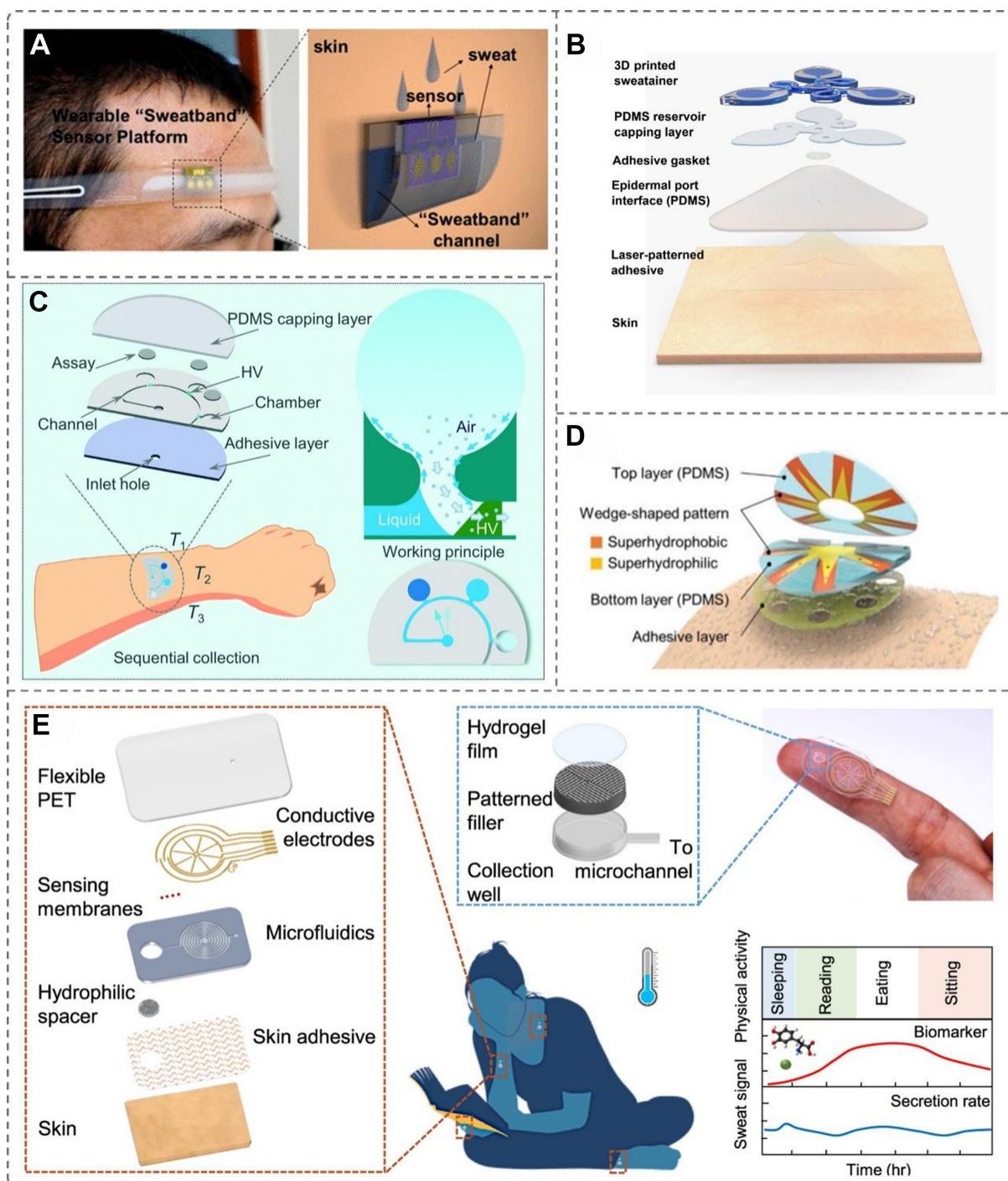


Figure 4. Structural design for sweat sampling in flexible sweat electronics. (A) Wearable sweatband channel for sweat collection. Reproduced with permission^[55]. Copyright 2017, American Chemical Society; (B) Sweat tainer system for sweat collection. Reproduced under the terms and conditions of the CC BY^[56]. Copyright 2023, Author(s), published by The American Association for the Advancement of Science; (C) The chamber with hydrophobic valves to reduce sweat evaporation and contamination. Reproduced with permission^[57]. Copyright 2020, Royal Society of Chemistry; (D) Cactus spines inspired patch with wettability patterned channels. Reproduced with permission^[58]. Copyright 2021, Wiley-VCH; (E) Hydrophilic fillers into the sensing channel to enhance the uptake of sweat. Reproduced under the terms and conditions of the CC BY^[16]. Copyright 2021, Author(s), published by Springer Nature.

wettability patterned channels inspired by cactus spines. The patch features a hierarchical microstructured/

nanostructured surface with wedge-shaped wettability-patterned channels. This design allows for efficient sweat transfer without retention inside the channels, resulting in higher sweat-collecting efficiency and faster sensing time [Figure 4D]^[58]. In order to facilitate efficient small-volume sweat collection and analysis during rest, Nyein *et al.* incorporated hydrophilic fillers into the sensing channel. This integration enhances the rapid uptake of sweat, reducing the necessary time for sweat accumulation and enabling real-time measurements [Figure 4E]. A microfluidic channel with pillars in the sweat collection center is designed to optimize the sweat flow conditions and enable a better sampling procedure for quick detection of reservoir filling^[16].

Sweat inducing methods

Regarding techniques for stimulating sweat production, exercise, such as running and cycling, is a commonly used method for sweat analysis [Figure 5A and B], where various devices monitor biological markers in sweat during physical activity^[59,60]. However, some limitations remain, such as the inability to engage in strenuous exercise, inconvenience for individuals with mobility issues, and challenges for the elderly. Therefore, there is a need to explore alternative methods of inducing sweat for research and analysis.

Alternatively, wearable sensors can be engineered to use iontophoresis to locally induce sweating. This makes it possible to obtain equilibrium sweat without exercising, which makes it perfect for medical checks when a person is sedentary. Hydrogels with pilocarpine medication are applied and activated below the skin, prompting sweat gland activation, and then the wearable sensors detect the released perspiration [Figure 5C]^[61]. A tattoo-based alcohol sensor is developed by Kim for noninvasive detection of alcohol in perspiration. The wearable alcohol sensing platform combines flexible wireless electronics with an iontophoretic-biosensing temporary tattoo device [Figure 5D]^[62]. Recently, Xu *et al.* proposed a novel iontophoresis-based sweat collection powered by a triboelectric nanogenerator (TENG). When a TENG is tapped, it will generate an electric field to facilitate the penetration of the skin and activate sweat production by delivering carbachol through iontophoresis. This study indicates a direct correlation between the amount of sweat and the applied force, where external force ranging from 1 to 9 N resulted in sweat volumes ranging from 2.7 to 5.9 $\mu\text{L}\cdot\text{cm}^{-2}$ in a 30-minute period [Figure 5E]. However, due to potential skin injury from repeated iontophoretic current application and noisy artifacts from excessive contact, this method is more suitable for situations where it is preferable to employ it once rather than for ongoing monitoring purposes^[63].

Recent advancements in wearable sweat devices have successfully integrated sweat sampling, storage, and analysis into multifunctional platforms. Here, we also present an extensive overview of the advantages and persistent obstacles related to various sweat sampling methods in Table 1^[16,44-46,49,50,52,54-58,64].

SWEAT-BASED BIOSENSORS

Eccrine sweat, excreted directly onto the skin surface, is easily accessible and noninvasive. It consists mainly of water, along with metabolites such as glucose, lactate, uric acid, electrolytes such as Na^+ , K^+ ions, *etc.*, making it relevant for assessing human health status^[10,26,42,65]. Here, the concentration of common analytes in sweat (sweat volume, various ions, metabolites, nutrients, hormones, proteins, and so on) and their association with related diseases is summarized in Table 2^[6,9,16,18,27,33,61,66-97]. For instance, an abnormal sweat rate may lead to dehydration, while deviations in K^+ concentration from the normal range can indicate conditions such as hypokalemia, hyperkalemia, irregular heartbeat, arrhythmia, muscle cramps, and even renal failure^[66-68,72,74]. The real-time detection of various physiological markers (glucose, lactate, uric acid, Na^+ , K^+ and NH_4^+) can also provide insights into the emotional fluctuations of the human body. These

Table 1. Summary of sweat sampling methods

Sweat sampling method		Sampling position	Advantages	Disadvantages	Application	Ref.
Traditional methods	Whole body washdown technique	Whole body	<ul style="list-style-type: none"> Measuring body's electrolyte loss in passive exposure 	<ul style="list-style-type: none"> In a controlled laboratory environment Complex steps 	Sweat loss, sweat electrolyte composition	[44]
	Absorbent patch	Arm	<ul style="list-style-type: none"> No disruption to the regular perspiration process Low cost Flexible 	<ul style="list-style-type: none"> Contamination from skin Need centrifuge extraction in Biochem Lab 	Sweat Na ⁺ and K ⁺ analysis	[46]
	Macroduct	Arm	<ul style="list-style-type: none"> No sample leakage or contamination Unrestricted working environment 	<ul style="list-style-type: none"> Possible analyte degradation between sampling and testing 	Cystic fibrosis diagnosis	[64]
	Pocket-shape drape	Back	<ul style="list-style-type: none"> Reduce contamination 	<ul style="list-style-type: none"> Complex steps Need a sauna environment 	Sweat glucose detection	[45]
Skin-electronics-based sweat sampling methods	Sponge	Arm	<ul style="list-style-type: none"> Collection of sweat through capillary forces without requiring intricate microfluidic handling systems 	/	Colorimetric measurement of sweat components	[49]
	Janus PE/NC textile	Upper body	<ul style="list-style-type: none"> Directional sweat transport properties Comparable water wicking and air permeability to traditional clothes 	/	Human body moisture and thermal management	[50]
	Filter paper	Arm	<ul style="list-style-type: none"> Mass customization Low cost 	<ul style="list-style-type: none"> Occlusive dressings can cause moisture buildup on the skin, potentially leading to sweat duct blockage and suppression 	Colorimetric indicator of sweat rate	[52]
	PVA hydrogel	Fingertip	<ul style="list-style-type: none"> No requirement for intense exercise or iontophoretic sweat stimulation 	<ul style="list-style-type: none"> Need a periodic blood calibration 	Sweat glucose monitoring	[54]
	Sweatband	Forehead	<ul style="list-style-type: none"> Portable 	<ul style="list-style-type: none"> Potential contamination 	Sweat sodium monitoring	[55]
	Sweatainer	Arm	<ul style="list-style-type: none"> Multidraw simplifies collection of multiple sweat samples for analysis 	/	Colorimetric assays for in situ biomarker analysis	[56]
	Microfluidic channel	Wrist, finger, arm	<ul style="list-style-type: none"> Continuous sampling and real-time analysis Convenient to mount on any part of the body 	<ul style="list-style-type: none"> Reusability and durability 	Sweat glucose, lactate, pH, Cl ⁻ , ethanol and levodopa monitoring	[16,57,58]

PE: Polyester; NC: superhydrophilic nitrocellulose; PVA: polyvinyl alcohol.

findings underscore the significance of sweat-based biosensors^[98]. Recently, numerous reviews have also provided summaries of the advancements in sweat-based sensors^[28,99-103]. This review specifically focuses on discussing several noteworthy sweat sensors based on metabolites, ions, drugs, and sweat volume, as indicated in Table 3^[18,54,61,81,97,104-109].

Table 2. Analytes in sweat and related health status

	Analytes	Normal range in sweat	Related health status	Ref.
Volume	Sweat rate	0.72-3.65 mg·cm ⁻² ·min ⁻¹	Dehydration	[66-68]
Ions	Na ⁺	10-100 mM	Hyponatremia; hypernatremia; identification of dehydration; heat stress; dehydration	[68-72]
	Cl ⁻	10-100 mM	Hypochloremia; hyperchloremia; cystic fibrosis diagnosis	[68,73]
	K ⁺	1-18.5 mM	Hypokalemia diagnosis; hyperkalemia diagnosis; irregular heartbeat and arrhythmia diagnosis; renal failure monitoring; muscle cramps	[68,72,74]
	NH ₄ ⁺	0.1-1 mM	Changing from an aerobic state to an anaerobic state; hepatic disorder diagnosis	[75]
	Ca ²⁺	0.41-12.4 mM	Hypocalcemia; hypercalcemia; chronic kidney diseases; mineral bone disorder; cirrhosis	[72,76]
	Zn ²⁺	100-1,560 µg·L ⁻¹	Diarrhea; pneumonia; liver damage; zinc poisoning	[77,78]
	pH	3-8	Cystic fibrosis; hydration; dermatitis; ichthyosis; fungal infections; wound healing	[33,68,69]
	Cd ²⁺	< 100 µg·L ⁻¹	Respiratory tract, liver and kidney problems	[77]
	Hg ⁺	< 100 µg·L ⁻¹	Hunter-Russell syndrome; minamata disease; acrodynia uremia	[77]
	Pb ²⁺	< 100 µg·L ⁻¹	Lead poisoning; infertility; memory loss; high blood pressure	[77]
	Cu ²⁺	100-1,000 µg·L ⁻¹	Anemia; osteoporosis; heart and kidney failure; brain disease and disorder; Wilson's disease, liver damage	[77]
	Metabolites	Glucose	10-200 µM	Diabetes and prediabetes monitoring; hypoglycemia management
Lactate		2-30 mM	Lactic acidosis diagnoses; tissue hypoxia; respiratory disease	[68,80,81]
Urea		1.8-46 mM	Kidney failure diagnosis; uraemia diagnosis	[82-84]
Uric acid		2-10 mM	Gout management; cardiovascular and kidney disease	[6,27,76]
Nutrients	Ascorbic acid (vitamin C)	10-50 µM	Uric acid stone diagnosis; scurvy diagnosis; chronic inflammation	[85]
	Tyrosine	0.2-0.4 mM	Metabolic disorders; neuropsychiatric and eating disorders; liver diseases	[6]
	Tryptophan	0.055-0.08 mM	Inflammation-associated disorders	[86]
Hormones	BCAAs	0.2-1 mM	Hepatocellular carcinoma; muscle wasting disorders; chronic renal failure	[87,88]
	Cortisol	0.1-20 × 10 ⁻³ mM	Pressure level monitoring; depressive disorder diagnosis; cardiovascular diseases	[27,89]
	Testosterone	0.8-1.6 × 10 ⁻⁶ mM	Depression	[90]
Proteins	Neuropeptide Y	50-200 pg·mL ⁻¹	Major depression disorder; management of chronic anxiety disorders	[91]
	C-reactive protein	4.2-250 × 10 ⁻⁹ mM	Chronic inflammation	[9,27]
	Interleukin 6	5-15 pg·mL ⁻¹	Insulin activity; immune responses in cancer therapy	[93]
	Interleukin 8	4.2 ± 1.7 pg·mL ⁻¹	Role as a major inflammatory mediator; physiological homeostatic functions	[94]
Drugs	TGF-β	3.7 ± 1.6 pg·mL ⁻¹	Cell growth, differentiation to the regulation of immune responses	[94,95]
	Levodopa	< 2.5 × 10 ⁻³ mM	Parkinson's disease management	[16,27]
	Acetaminophen	< 50 × 10 ⁻³ mM	Chronic liver disease	[27,96]
Others	Caffeine	/	Coronary syndrome; hypertension; depression	[18]
	Ethanol	2.5-22.5 mM	Alcohol consumption detection; alcohol intoxication diagnosis; alcohol cardiomyopathy diagnosis	[92]
	Nicotine	/	Nicotine poisoning	[97]

BCAAs: Branched-chain amino acids; TGF-β: transforming growth factor beta.

Metabolites detection

Among wearable sweat sensors, the detection of metabolites has seen significant advancements and widespread use. This capability offers valuable insights into body glucose levels, tissue hypoxia, body hydration, *etc.* Glucose and lactate are the two most studied metabolites providing physiological information on human health status. Sempionatto *et al.* developed finger-touched sweat electrochemical

Table 3. Summary of technical capabilities of flexible sweat sensors

Analytes	Recognition element	Sensing technique	Linear Range	Sensitivity	Whether to measure continuously	Ref.	
Glucose	Glucose oxidase	Chronoamperometry	0-450 μM	$2.89 \text{ nA}\cdot\mu\text{M}^{-1}$	No	[54]	
	rGO/PU/Au	Chronoamperometry	0.5 nM to 10 mM	$140 \mu\text{A}\cdot\text{mM}^{-1}\cdot\text{cm}^{-2}$	Yes	[104]	
Lactate	Lactate oxidase	Chronoamperometry	0-28 mM	$96 \text{ nA}\cdot\text{mM}^{-1}$	Yes	[81]	
	Lactate oxidase	Chronoamperometry	0-15 mM	$90 \text{ nA}\cdot\text{mM}^{-1}\cdot\text{mm}^{-2}$	Yes	[105]	
	Lactate oxidase	Potentiometry	0-15 mM	$2.48 \text{ mV}\cdot\text{mM}^{-1}$	Yes	[106]	
Ions Na^+	Na Ion-selective membrane	Potentiometry	10-160 mM	63.2 mV per decade	Yes	[61]	
	Na Ion-selective membrane	Potentiometry	0.1-100 mM	$54.2 \pm 1.3 \text{ mV}$	Yes	[107]	
Cl^-	Ag/AgCl electrodes	Potentiometry	10-160 mM	55.1 mV per decade	Yes	[61]	
	Ag/AgCl electrodes	Potentiometry	1-100 mM	$-63.0 \pm 2.4 \text{ mV}$	Yes	[107]	
K^+	K Ion-selective membrane	Potentiometry	0.1-100 mM	$56.8 \pm 2.5 \text{ mV}$	Yes	[107]	
pH	Ion-selective membrane	Potentiometry	4-7.5	$50.1 \pm 0.5 \text{ mV}$	Yes	[107]	
	PANI	OCP	4-8	$-33.82 \text{ mV}\cdot\text{pH}^{-1}$	Yes	[108]	
Drugs	Psychoactive drugs	Apt1, Apt2 aptamers	Potentiometry	0.001 to 5 μM	/	Yes	[108]
	Caffeine	Carbon nanotube/Nafion Film	DPV	0-40 μM	$110 \text{ nA}\cdot\text{mM}^{-1}$	Yes	[18]
	Nicotine	CYP2B6	Chronoamperometry	0-30 μM	$4.3 \text{ nA}\cdot\text{mM}^{-1}$	Yes	[97]
	Carbamazepine	NiSe_2	Chronoamperometry	50 nM to 10 μM	$65.65 \mu\text{A}\cdot\text{mM}^{-1}$	No	[109]

rGO: Reduced graphene oxide; PU: polyurethane; PANI: polyaniline; OCP: open-circuit potential; DPV: differential pulse voltammetry; CYP2B6: cytochrome P450 2B6.

sensors featuring a PVA hydrogel as the sweat collection component. These sensors employ Prussian Blue (PB) as a transducer to identify the hydrogen peroxide generated through the enzyme-catalyzed glucose reaction. With the integration of an individualized sweat-to-blood conversion algorithm, these sensors enable fast, dependable, and user-friendly self-assessment of glucose levels in fingertip sweat [Figure 6A]^[54]. A textile-based sweat glucose sensor is presented by Toi *et al.*, which utilizes a unique wrinkled, stretchable nanohybrid fiber (WSNF) as the electrode. This WSNF comprises a hybrid fiber constructed of reduced graphene oxide (rGO) and polyurethane, with Au nanowrinkles partially covering its surface. Because of the synergistic impacts of these nanowrinkles and the oxygen-containing functional groups in the rGO-supporting matrix, the WSNF demonstrates remarkable electrocatalytic activity. These effects significantly augment the dehydrogenation stage during glucose oxidation. Consequently, the WSNF electrode demonstrates a remarkable response to glucose, featuring a sensitivity of $140 \mu\text{A}\cdot\text{mM}^{-1}\cdot\text{cm}^{-2}$ and a detection limit of 500 nM [Figure 6B]^[104].

The ability to detect fluctuations in lactate levels in real-time can indicate physical stress and may aid in identifying shifts from aerobic to anaerobic states when there is an oxygen shortage and need for extra energy, as happens during exercise. Figure 6C showcases a lactate sensor patch created through screen printing on a flexible polyester sheet, designed to perfectly adapt to the intricate contours of the skin, guaranteeing a distinct signal. The lactate measurement part of the patch features a modified electrode coated with a bio-compatible layer [lactate oxidase (LOx)-modified PB], with a sensitivity of $96 \text{ nA}\cdot\text{mM}^{-1}$ ^[81]. Saha *et al.* introduced a seamless platform for continuously monitoring sweat lactate, which integrates an osmotic hydrogel for sweat collection, a microfluidic channel made of paper for sweat transportation, a screen-printed electrochemical sensor for lactate detection, and a tailor-made wireless wearable potentiostat system. At rest, the osmosis hydrogel enables the collection of sweat samples without external power. Simultaneously, the continuous evaporation in the paper channel allows for prolonged sensing using fresh sweat. Through strategic placement, lactate sensors offer nearly instant sensing capabilities using minimal

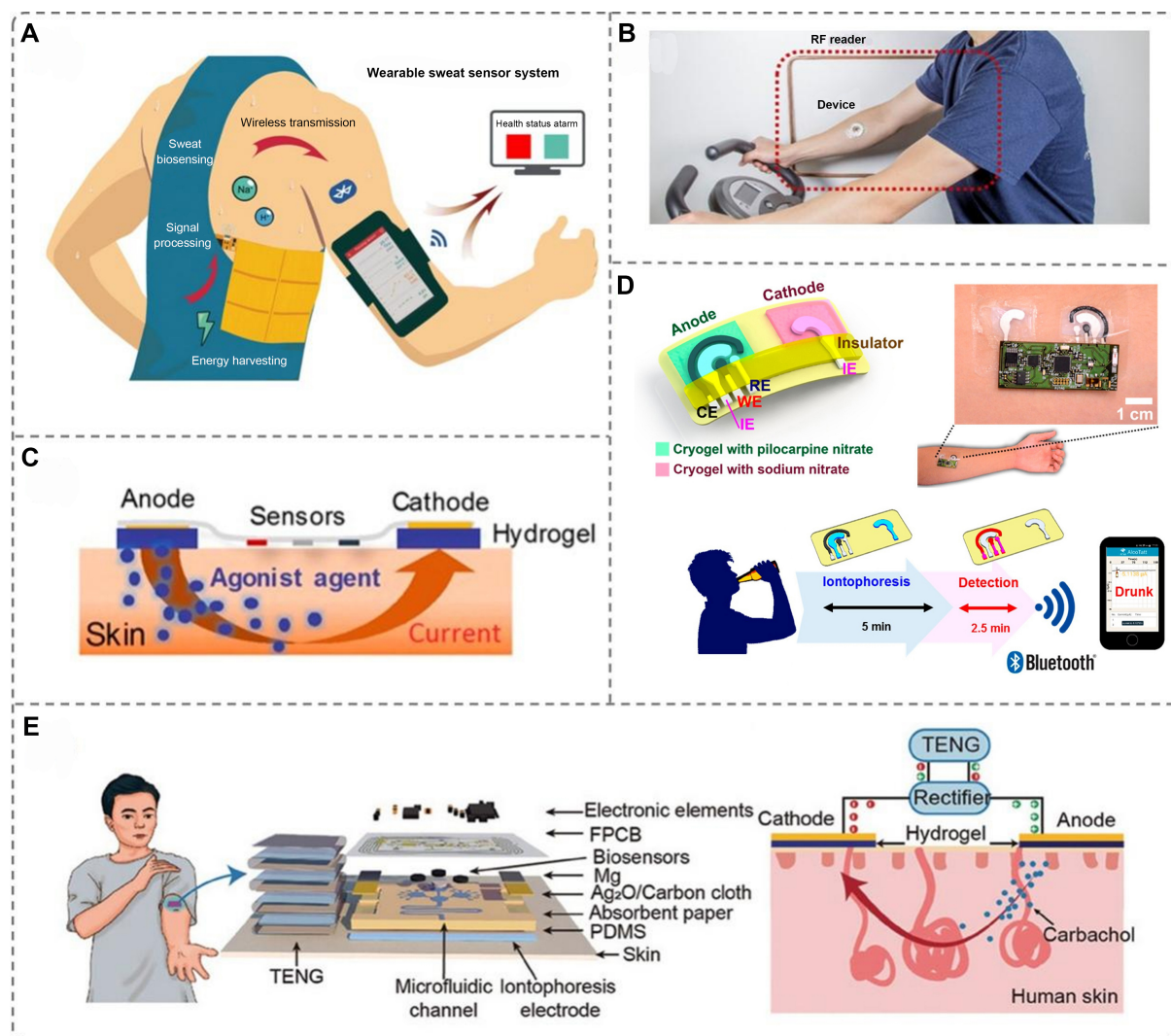


Figure 5. Common ways to induce sweat. Physical activity such as (A) running. Reproduced under the terms and conditions of the CC BY-NC^[59]. Copyright 2020, Author(s), published by The American Association for the Advancement of Science; (B) cycling. Reproduced under the terms and conditions of the CC BY-NC^[60]. Copyright 2019, Author(s), published by The American Association for the Advancement of Science; (C) Schematic diagram of iontophoresis methods. Reproduced with permission^[61]. Copyright 2017, National Academy of Sciences Publishing Group; (D) Tattoo-based iontophoretic-biosensor. Reproduced with permission^[62]. Copyright 2016, American Chemical Society; (E) Triboelectric nanogenerator Enabled Sweat Extraction. Reproduced with permission^[63]. Copyright 2023, Wiley-VCH.

sweat volume, while the custom-built potentiostat system allows ongoing monitoring while consuming minimal power [Figure 6D]^[105]. Based on biofuel cells (BFCs), Huang *et al.* presented an enzymatic self-powered sensor that enables in situ detection of glucose and lactate in sweat. The ultra-thin, flexible PDMS microfluidic channels collect sweat effectively and retain stable performance even when stretched up to 30%. The soft sweat sensors exhibit a sensitivity of $2.48 \text{ mV}\cdot\text{mM}^{-1}$ for lactate detection and $0.11 \text{ mV}\cdot\mu\text{M}^{-1}$ for glucose detection [Figure 6E]^[106].

In addition to monitoring glucose and lactate levels, significant progress has been achieved in advancing sensors for a range of other metabolites such as uric acid, alcohol, and more, offering a deeper understanding of an individual's health condition. Hu *et al.* proposed a remarkable sweat monitoring device

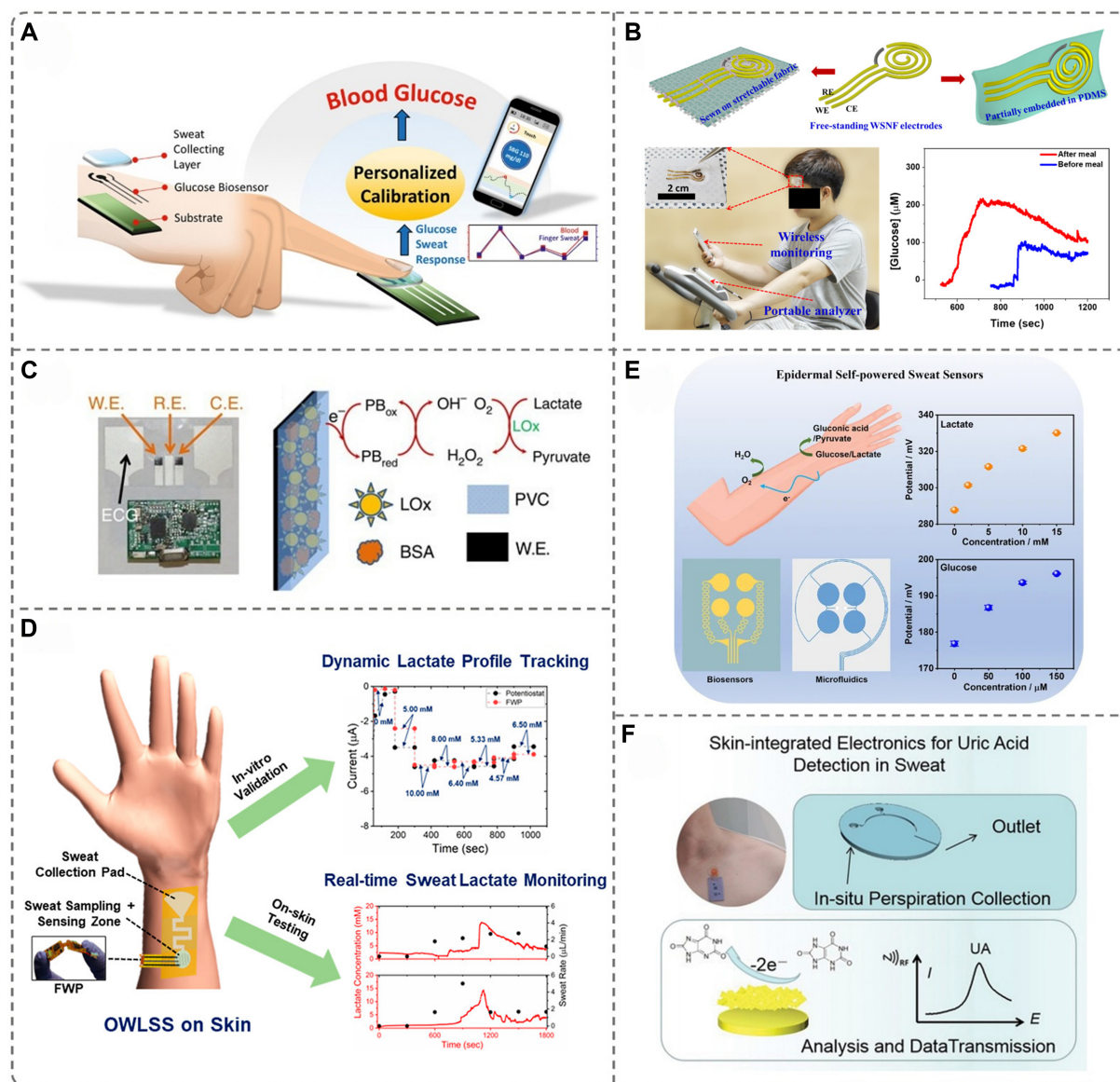


Figure 6. Flexible sweat sensors for metabolite monitoring. (A) A fingertip touch sensor for sweat glucose monitoring. Reproduced with permission^[54]. Copyright 2021, American Chemical Society; (B) A textile-based sweat glucose sensor. Reproduced with permission^[104]. Copyright 2019, American Chemical Society; (C) Sweat sensor for lactate detection. Reproduced under the terms and conditions of the CC BY^[81]. Copyright 2016, Author(s), published by Springer Nature; (D) Wireless wearable electrochemical sensing platform for continuous lactate monitoring. Reproduced with permission^[105]. Copyright 2022, American Chemical Society; (E) Glucose and lactate monitoring by self-powered biosensor. Reproduced with permission^[106]. Copyright 2021, Springer Nature; (F) Skin-integrated electronics for sweat uric acid detection. Reproduced under the terms and conditions of the CC BY^[76]. Copyright 2023, Taylor & Francis Online.

that integrates a uric acid monitoring system with a PDMS-based microfluidic system. This flexible and wearable device allows for on-site perspiration collection, analysis, and wireless data transmission. The uric acid sensor demonstrated a detection range of 5-200 μM and a detection limit of 1.79 μM . This novel technology provides a valuable diagnostic tool for routine health monitoring, particularly for patients with conditions such as gout, cardiovascular diseases, and renal diseases [Figure 6F]^[76]. Kim *et al.* reported a tattoo-based alcohol monitoring platform that combines sweat-inducing iontophoresis with an amperometric enzymatic biosensing method. This alcohol biosensor obtained a detection range of 0-36 mM and a sensitivity of $0.362 \pm 0.009 \mu\text{A}\cdot\text{mM}^{-1}$, which can provide real-time status of personal alcohol

consumption in practice^[62]. All these developments contribute to the field of personalized health monitoring using sweat-based metabolite analysis.

Ions and sweat volume detection

Sweat can also provide significant perspectives into an individual's health condition by reflecting the body's amount of salt and water metabolism. For instance, dehydration, cramping in the muscles, and hyponatremia can result from excessive sodium and potassium loss. Emaminejad *et al.* proposed a wearable electrochemical sensor [Figure 7A] as a wristband. It safely extracts sweat using improved iontophoresis, allowing thorough analysis of specific elements such as Na⁺ and Cl⁻. The system wirelessly controls sweat production and provides instant on-site measurements. Specialized electrochemical methods and ion-selective membranes enhance electrode stability and selectivity. This advanced system enables easy access to abundant sweat samples for widespread health monitoring^[61]. Parrilla *et al.* reported a wearable potentiometric ion sensor (WPIS) to measure ions in sweat. These sensors track pH, Cl⁻, K⁺, and Na⁺ using a flexible sampling cell. The electronic part is screen-printed on a flexible substrate, and electrodes are enhanced utilizing multi-walled carbon nanotubes (MWCNTs) and a selective membrane. The sampling cell ensures accurate sweat capture without contamination or evaporation issues [Figure 7B]^[107].

As for the sweat volume monitoring, a flexible, adhesive patch with sticker-like properties is attained by combining multiple layers of microfluidics, reservoirs for dyes and bioassays, a top layer featuring color reference stripes, and a skin adhesive layer underneath, as illustrated in Figure 7C. A specified sweat collecting location can yield around 130 μL of sweat for Microchannel 1. Perspiration and an orange dye combine to create a highly visible propagation down the channel, making it possible to quickly analyze and estimate the volume of perspiration. The low bending stiffness and thin shape of the device allow for mechanical deformations, improving wearability during strenuous physical activity^[47]. Then, Wang *et al.* introduced an innovative wearable sensor for calibration-free assessment of regional sweat rate and total electrolyte level. By employing a compact vertical channel, integrated conductance electrodes, and an absorbent layer, the microfluidic-based sweat sensor device achieves controlled sweat behavior and sequential detection. The sweat is collected in small volumes, contacts the electrodes, and evaporates quickly. Real-time recordings generate a square-wave conductance profile, providing information on sweat rate and electrolyte concentration. The sensor can measure sweat rate within the range of 0.5-20 $\mu\text{L}\cdot\text{min}^{-1}\cdot\text{cm}^{-2}$ and electrolyte levels between 1-200 mM, with minimized flow resistance [Figure 7D]^[110]. A tape-free device is introduced, featuring a 3D-printed sweat collector with a concave surface securely strapped onto the skin. Optimized for efficient sweat capture and conformal contact, the collector interfaces with embedded electrodes and a fluidic microchannel for continuous sweat rate monitoring. It accurately measures long-term exercise-induced sweat rates from various body locations, offering insights into the correlation between sweat profiles and overall fluid loss. With easy installation and reusability, it can be seamlessly integrated with a watch band [Figure 7E]^[111]. Preventing damage to electronic components caused by sweat is of utmost importance for effectively utilizing sweat sensors. Recently, extensive research has been conducted to address this issue. One promising approach involves implementing sealing processes that effectively block any liquid from entering the internal electronic components^[61,79]. Additionally, integrating intelligently designed microfluidic channels or permeable materials aids in efficiently directing sweat toward the sensor or detection unit, thereby significantly reducing the likelihood of sweat reaching and potentially harming the electronic components of the wristband^[112,113].

Drugs detection

Sweat analysis has also become a vital tool for drug analysis, finding applications in clinical therapies, drug misuse testing, doping control, and digital health monitoring^[26,114]. The wearable electrochemical aptasensor [Figure 7F] detects drugs in sweat with good precision and sensitivity. It utilizes an array of single and dual

Apt2. With secure skin adherence, this flexible sensor enables monitoring of psychoactive drug intake during sweating, combining precise aptamers and electrochemistry for fast and accurate identification^[108]. Caffeine, a widely consumed drug found in coffee, tea, and various commercial products, can result in health issues such as coronary syndromes, high blood pressure, and depression when taken excessively. In official athletic competitions, it is considered an ergogenic drug, and its presence in urine is tested before tournaments. The triple-electrode array [Figure 7G] utilizes a carbon electrode modified with carbon nanotubes (CNTs)/Nafion films as the working electrode, along with a carbon counter electrode and an Ag/AgCl reference electrode. Caffeine detection via differential pulse voltammetry (DPV) results in a distinct peak around 1.4 V, providing a quantitative measure of caffeine concentration in sweat. This device effectively monitors sweat caffeine levels, correlating with dosage and revealing physiological patterns associated with caffeine intake^[18]. A wearable sweatband is also being proposed as an effective solution for monitoring nicotine levels in sweat, allowing for a quantitative assessment of an individual's exposure to smoking. The working electrode of the sweatband is constructed using gold nanodendrites and is functionalized with cytochrome P450 2B6 (CYP2B6), an enzyme that can oxidize nicotine. This oxidation process converts sweat nicotine into a nicotine iminium ion, resulting in a measurable current. By analyzing the amperometric responses of the sensor, it becomes possible to quantify nicotine concentrations in sweat. The presented nicotine sensors demonstrate a sensitivity of $4.3 \text{ nA}\cdot\text{mM}^{-1}$ and a linear range of $0\text{-}30 \text{ }\mu\text{M}$ ^[97]. Carbamazepine (CBZ) is a commonly prescribed neurological therapeutic drug used to treat a range of conditions, including psychomotor seizures, trigeminal neuralgia, clonic seizures, partial seizures, and other related disorders. Veeralingam *et al.* have developed a cost-effective and flexible amperometric sensing platform for detecting its levels in human sweat. This innovative platform employs NiSe₂ nanoclusters as the working electrode. By utilizing their large surface area, these nanoclusters exhibit an impressive sensitivity of $65.65 \text{ }\mu\text{A}\cdot\text{mM}^{-1}$, covering a wide concentration range from 50 nM to $10 \text{ }\mu\text{M}$ ^[109]. In conclusion, sweat analysis has become increasingly important for drug detection and monitoring, and the promising results from recent studies emphasize its potential for application in point-of-care medical diagnostics.

SWEAT-BASED ENERGY HARVESTERS

Advancements in flexible electronics enable detailed physiological data collection. Traditional batteries pose challenges with their bulkiness, inflexibility, and hazardous components. Recently, significant progress has been made in powering flexible electronics with innovative methods. One promising approach is utilizing near field communication (NFC) for efficient energy transfer in a sweat sensing system, enabling the wireless power transmission from an external source to the device and eliminating the need for physical connections or bulky batteries^[115-117]. Another exciting avenue is leveraging energy from the sweat itself to power flexible electronics. Sweat contains various chemical components, including electrolytes and metabolites, that can be harnessed to generate electrical energy^[28,29,41]. What is more, it is a naturally occurring bodily fluid constantly produced by our sweat glands, readily available and easily obtained^[118]. Additionally, utilizing sweat as an energy source is biocompatible and environmentally friendly^[66,113,119]. By converting the chemical energy present in sweat into electricity, these devices enable self-sustainability and reduce the dependence on traditional power sources. Here, we summarize the recent developments in BFCs, SABs, and SACs, which can be seamlessly integrated with sweat sampling and sensing modules, enhancing functionality while reducing risks associated with conventional batteries.

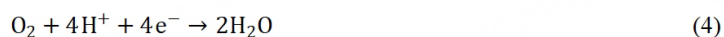
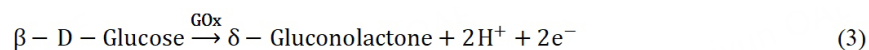
Sweat-based biofuel cells

Sweat-based BFCs are unique electrochemical devices that utilize biofluids as both electrolytes and fuel sources. They utilize bioelectrocatalytic reactions to generate electricity by harnessing the energy from redox-active metabolites found in sweat. Lactate, abundant in sweat at concentrations of $2\text{-}30 \text{ mM}$, is particularly important in energy generation^[26]. Typically, these BFCs use LOx as the anode, while the cathode incorporates oxygen reduction catalysts [Figure 8A]^[120]. The anode and cathode reactions can be

The enzyme-electrode interface is crucial for sweat-based BFCs. Electronic mediators enhance the ability of LOx to oxidize lactate by aiding electron transfer. Choice of mediators influences anode potential, determining the onset potential of oxidation. 1-methoxy-5-methylphenazinium methyl sulfate (1-methoxy PMS)^[121], tetrathiafulvalene (TTF)^[120,122-124], naphthoquinone^[125-130], and ferrocene derivatives^[131-133] are commonly used as the electronic mediators. Yu *et al.* developed an electronic skin powered by sweat lactate BFCs that utilizes the TTF as the redox mediator, demonstrating an open-circuit potential (OCP) of approximately 0.6 V and achieving the highest power output of around 3.5 mW·cm⁻² in 40 mM lactate solutions. The device exhibited exceptional stability, maintaining its performance over a continuous 60-hour operation^[124]. Yang *et al.* constructed a lactate BFC using a 1,4-naphthoquinone/MWCNT-modified bio-anode, which can deliver a power density of 62.2 ± 2.4 μW·cm⁻² under bending/torsion conditions [Figure 8B]^[130]. The leaching of enzymes influences the output performance and stability of BFCs. Adding biopolymers (such as chitosan) and polymers (such as Nafion) to the anode proves to be highly effective in safeguarding the enzymes and preventing leaching^[122,127,129]. The cathode facilitates the completion of the biofuel reaction through the oxygen reduction reaction (ORR). Platinum (Pt) and related alloys are commonly employed as catalysts to enhance the ORR in sweat^[35,134]. Biocatalysts such as bilirubin oxidase (BOD) are also excellent options for facilitating the ORR^[135,136]. The performance of the BOD reaction can be enhanced by molecules such as protoporphyrin IX, which can selectively orient the enzyme towards the T1 center of BOD, facilitating direct electron transfer with CNTs^[127].

In addition to lactate-based sweat BFCs, glucose and ethanol are two promising metabolites found in sweat that can be utilized as fuel sources. The working mechanisms are given in the following equations.

As for glucose, the anode and cathode reactions are respectively denoted as [Figure 8C]^[137]



Yin *et al.* developed a cotton textile-based BFC using bioanode and biocathode fibers for glucose oxidation and oxygen reduction. The cell achieved power densities of 48 μW·cm⁻² at 0.24 V and 216 μW·cm⁻² at 0.36 V with varying glucose concentrations. The flexible design maintained performance even when deformed, and a series connection of four cells illuminated an light-emitting diode (LED) at 1.9 V [Figure 8D]^[138].

As for ethanol, the reactions are written as [Figure 8E]^[139]



Sun *et al.* created a flexible BFC that captured energy from individuals after alcohol consumption, using ethanol as a biofuel. The BFC incorporated 3D coralloid nitrogen-doped hierarchical micromesoporous carbons aerogels (3D-NHCAs), alcohol oxidase (AOx), and terephthalaldehyde (TPA) on one screen-printed electrode (SPE) anode, and 3D-NHCAs, BOD, and TPA on another SPE electrode as biocathode. The extensive surface area of the electrode enhanced electrocatalytic performance, resulting in an output of 1.01 μW·cm⁻² during exercise [Figure 8E]^[139]. These advancements expand the range of biofuels derived from

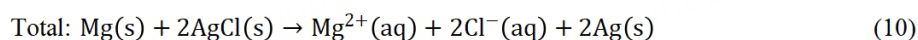
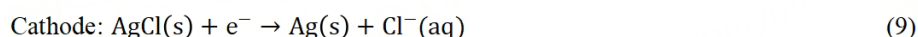
human sweat.

Microbial fuel cells (MFC) have recently become a promising method for harnessing energy from human sweat. This innovative approach involves utilizing bacteria as biocatalysts to effectively convert the chemical energy present in sweat into electrical power through bacterial metabolism [Figure 8F]^[140]. Mohammadifar *et al.* developed a flexible MFC that generates electricity from sweat using selected bacteria. The MFC can utilize either ammonia-oxidizing or common skin bacteria, offering long-term stability and self-sustaining features. The MFCs contain microorganisms with inherent abilities for self-assembly, self-repair, and self-maintenance. When triggered by human perspiration, the MFC achieved the highest power density of $41.74 \pm 5.35 \mu\text{W}\cdot\text{cm}^{-2}$ with freeze-dried *S. epidermidis* [Figure 8G]^[141]. The utilization of microbial energy for wearable electronics remains relatively unexplored, primarily due to concerns regarding the potential toxicity associated with microbial cells. The biocompatibility of these approaches requires further validation. Non-enzymatic fuel cells have also emerged as a promising alternative, offering potential for long-term operation in sweat-based platforms^[142,143]. Table 4 summarizes the recent developments of BFCs^[106,120,124,127,129,131,137-139,144]. All these developments underscore their potential in energy generation, with advantages including their renewable fuel sources, miniaturization potential, flexibility, and potential for integration into compact devices, enabling them to provide sufficient, sustainable, and biocompatible power for wearable electronics.

Sweat-activated battery

Batteries are essential for providing continuous power to flexible electronic devices owing to their high energy density, low self-discharge, and constant voltage output. Nevertheless, conventional batteries pose safety risks in wearable electronics due to the presence of toxic components (such as lead, cobalt, nickel, and so on) and flammable electrolytes. Rigid format is also a big hurdle when utilizing in flexible electronics. Therefore, plenty of power sources such as SABs, piezoelectric nanogenerators, TENGs, and flexible lithium batteries have been extensively explored to power the flexible electronics. Among these methods, SABs are a promising power source for wearable electronics due to their flexibility, biocompatibility, ease of use, and other merits.

Ortega *et al.* proposed a self-powered intelligent patch comprising a paper battery that is triggered by the absorption of sweat; the anode is magnesium, while the cathode is silver chloride [Figure 9A]. The reactions are given as



Here, the device not only acts as the SAB but also as a sensor, as the battery output is entirely contingent on conductivity and components of sweat, which can reflect the wearer's health status. This approach allows for the consolidation of the battery and sensor into a single unit^[145].

Ju *et al.* presented a sweat-activated yarn battery (SAYB) with a unique core-sheath structure. The SAYB used zinc (Zn) as the anode and carbon as the cathode. It could be triggered in just three seconds by a small amount of NaCl solution (1 μL , 100 mM); this swift activation was facilitated by the thin and hydrophilic cotton sheath of the SAYB. The battery achieved a high power density ($0.72 \text{ mW}\cdot\text{cm}^{-2}$) and energy capacity

Table 4. The summarization of sweat-based BFCs and their performance

Electrode		Fuel	OCP (V)	Power density	Ref.
Anode	Cathode				
FcMe ₂ -LPEI/LOx/TP-PTFE	AnMWCNT/BOx/TP-PTFE	Lactate	0.55	20 $\mu\text{W}\cdot\text{cm}^{-2}$	[131]
LOx/TTF/GNRs/GCE	BOD/ABTS/GNRs/GCE	Lactate	0.62	70.7 $\mu\text{W}\cdot\text{cm}^{-2}$	[120]
Chitosan/LOx/CNT-NQ/Au	Ag ₂ O/CNTs/Au	Lactate	0.5	1.2 $\text{mW}\cdot\text{cm}^{-2}$	[129]
LOx/1,4-NQ/MWCNT/Buckpaper	BOx/PPIX/MWCNT/Buckpaper	Lactate	0.74	1.2 $\mu\text{W}\cdot\text{cm}^{-2}$	[127]
LOx/TTF-MDB-CNTs/rGO/h-Ni	Pt alloy-decorated MDB-CNT	Lactate	0.6	3.5 $\text{mW}\cdot\text{cm}^{-2}$	[124]
LOx/graphene/Au	Lac/graphene/Au	Lactate	0.337	39.5 $\mu\text{W}\cdot\text{cm}^{-2}$	[106]
GOx/graphene/Au	Lac/graphene/Au	Glucose	0.195	2.16 $\mu\text{W}\cdot\text{cm}^{-2}$	[106]
PB/carbon cloth	GOx/carbon cloth	Glucose	0.298	16.7 $\mu\text{W}\cdot\text{cm}^{-2}$	[144]
GOx-TTF	BOx-ABTS	Glucose	0.62	656 $\mu\text{W}\cdot\text{cm}^{-2}$	[137]
GDH/A-CNT/PolyMG/A-CNT/fibers	BOD/A-CNT/PTFE-CNT/fiber	Glucose	0.55	48 $\mu\text{W}\cdot\text{cm}^{-2}$	[138]
AOx/TPA/3D-NHCAs/SPE	Box/TPA/3D-NHCAs/spe	Alcohol	0.55	1.01 $\mu\text{W}\cdot\text{cm}^{-2}$	[139]

BFCs: Biofuel cells; OCP: open-circuit potential; LPEI: linear polyethylenimine; LOx: lactate oxidase; TP-PTFE: Toray carbon paper-060 polytetrafluoroethylene; MWCNT: multi-walled carbon nanotube; BOx: bilirubin oxidase; TTF: tetrathiafulvalene; GNRs: graphene nanoribbons; GCE: graphene nanoribbons; BOD: bilirubin oxidase; ABTS: 2,2'-diazide-bis-3-ethylbenzothiazolin-6-sulfonic acid; CNT: carbon nanotube; NQ: naphthoquinone; PPIX: protoporphyrin IX; MDB: Meldola's blue; rGO: reduced graphene oxide; GOx: glucose oxidase; PB: Prussian Blue; GDH: glucose dehydrogenase; PolyMG: poly(methylene green); AOx: alcohol oxidase; TPA: terephthalaldehyde; 3D-NHCAs: 3D coraloid nitrogen-doped hierarchical microporous carbons aerogels; SPE: screen-printed electrode.

(15.3 mAh). It also demonstrated excellent durability, enduring 10,000 bending, 2,800 twisting, and 20 washing cycles without a discernible power reduction. This SAYB holds great potential for wearable healthcare and sports monitoring in smart garments [Figure 9B]^[146]. Liu *et al.* presented a soft, skin-integrated, and stretchable SAB that operates based on a straightforward single displacement reaction. In this system, when the KCl power-embedded cotton absorbs the sweat, zinc undergoes oxidation to form Zn²⁺ ions, while copper ions (Cu²⁺) are simultaneously reduced to copper (Cu). The whole system achieves a capacity of 42.5 mAh and a power density of 7.46 $\text{mW}\cdot\text{cm}^{-2}$, which can illuminate 120 LEDs continuously for more than 5 h. Additionally, it can power Bluetooth wireless technology, enabling the real-time recording of physiological signals for a duration exceeding 6 h [Figure 9C]^[147]. To further enhance the user-friendliness of SABs in wearable electronics, a SAB-based bandage is developed with a power density of 16.3 $\text{mW}\cdot\text{cm}^{-2}$ and an energy capacity of 74.4 mAh. The open circuit voltage of the SAB is 1.41 V, and its short circuit current is 53.4 mA for over 3.5 h. This bandage can power a wireless health monitoring platform for 1.2 h, enabling the recording of physiological signals. Its mechanical performance ensures stable output even when bent or twisted at various angles [Figure 9D]^[148]. Huang *et al.* proposed a garment-based microelectronics powered by SABs. This SAB cell has a thickness of 1.25 mm and exhibits outstanding biocompatibility. Based on the Mg/O₂ reaction principle, the battery has an open circuit voltage of 1.54 V, a short circuit current of 16.91 mA, a capacity of 14.33 mAh, and a power density of 3.17 $\text{mW}\cdot\text{cm}^{-2}$. The entire platform can be integrated as a pad into the head, elbow, or knee, enhancing user compliance with flexible electronics [Figure 9E]^[69]. Additionally, in order to enhance the performance of SABs, sufficient sweat is crucial. Wu *et al.* addressed this by combining bio-inspired microfluidics with SABs. Their device can collect human sweat within seconds (114 $\mu\text{L}\cdot\text{s}^{-1}$), resulting in a remarkable power density of 122 $\text{mW}\cdot\text{cm}^{-2}$ and a discharge capacity of 8.33 mAh [Figure 9F]^[149]. Table 5 summarizes the recent developments of SABs^[69,146-152]. These advancements showcase the impressive power capabilities achieved by SABs, thereby expanding the horizons for integrating power sources and sweat sensors into a unified system. This integration creates real-time, portable, and intelligent wearable sensing systems, unlocking a realm of new possibilities.

Table 5. The summarization of sweat-based SABs and their performance

Anode	Electrode		OCP (V)	Power density	Ref.
	Cathode				
Mg	LIGA@MnO ₂		1.5	6.31 mW·cm ⁻²	[150]
Mg	Ag ₂ O		1.8	122 mW·cm ⁻²	[149]
Mg	Ni/graphene foam		1.41	16.3 mW·cm ⁻²	[148]
Mg	Graphene		1.54	3.17 mW·cm ⁻²	[69]
Zn foil-wrapped yarn	Carbon-black-modified yarn		1	33.1 μW·cm ⁻²	[151]
Zn-wire	Carbon		1	1.72 mW·cm ⁻²	[146]
Zn	Ag ₂ O		-1	3.47 mW·cm ⁻²	[152]
Zn	CuSO ₄		0.93	7.46 mW·cm ⁻²	[147]

SABs: Sweat-activated batteries; OCP: open-circuit potential; LIGA@MnO₂: laser-induced PI/gelatin based graphene anchored with manganese dioxide.

Sweat-activated supercapacitor

Supercapacitors offer advantages over batteries, such as high power density, fast charge-discharge rates, and long cycling life. Traditional supercapacitors use toxic electrolytes, requiring special packaging for safety. In contrast, SASs utilize biocompatible biological fluids such as sweat as electrolytes. This section explores the emerging field of SASs and their potential for energy storage. Luo *et al.* devised an on-skin supercapacitor integrated into garments that harvests energy from sweat during sports^[153]. It utilizes a NaCl electrolyte and a polyaniline (PANI)/CNT electrode, offering an extended potential window of 0.8 to 1.4 V, with the energy density at 112.1 mF·cm⁻² (3.0 M NaCl) and 110.5 mF·cm⁻² (1.0 M NaCl). A sweat-charging watchband integrates four supercapacitors for effective charging up to 3.2 V [Figure 10A]. Manjakkal *et al.* introduced a flexible supercapacitor based on sweat for applications in wearables and smart textiles. Sweat serves as the electrolyte, and the active electrode is polypyrrole/poly (3,4-ethylenedioxythiophene):poly (styrenesulfonate) (PEDOT:PSS). Because of the redox reactions of PEDOT:PSS and electrochemical double-layer capacitance, the supercapacitor covered with PEDOT:PSS on cellulose/polyester cloth exhibits high capacitance. It attains a weight-specific capacitance of 8.94 F·g⁻¹ and area-specific capacitance of 10 mF·cm⁻² at 1 mV·s⁻¹ in sweat equivalent solution. Tested with real human sweat, the supercapacitor shows an energy density of 0.25 Wh·kg⁻¹ and a power density of 30.62 W·kg⁻¹, providing a safe and sustainable power solution for wearables [Figure 10B]^[154]. The sweat-based yarn biosupercapacitor (SYBSC) utilizes hydrophilic cotton fibers wrapped around stainless steel yarns modified with PEDOT:PSS, forming symmetrical electrodes. It attains a high areal capacitance of 343.1 mF·cm⁻² at a current density of 0.5 mA·cm⁻². The device maintains its capacitance at 68% after 10,000 charge-discharge cycles and 73% after 25 cycles of machine washing. When integrated with yarn-based self-charging power units and pH sensing fibers, it creates a comprehensive sensing textile triggered by sweat, allowing for real-time monitoring of pH levels in sweat generated during physical activity [Figure 10C]^[37].

The power requirements of a complete sweat-based platform typically fall within the range of nanowatts (nW) to milliwatts (mW). The existing sweat-based energy generators, such as BFCs and SABs, can generate maximum voltages of 1.8 V and 122 mW·cm⁻², respectively. This voltage and power output are adequate to power certain sensors and related devices for a few minutes. Here, we summarize the recent advancements in sweat-based BFCs and SABs and the typical power requirements for wearable devices [Figure 11A and B]. Additionally, Figure 11C demonstrates the significant power density consumption of bioelectronics systems, thereby confirming the viability and effectiveness of sweat-based energy harvesters^[155]. However, multifunctional sensing capabilities and additional components such as iontophoresis electrodes and wireless transmission modules may require higher energy levels to operate effectively. Furthermore, the performance of the BFCs, SABs, and SASs can indeed vary due to differences in sweat composition and pH

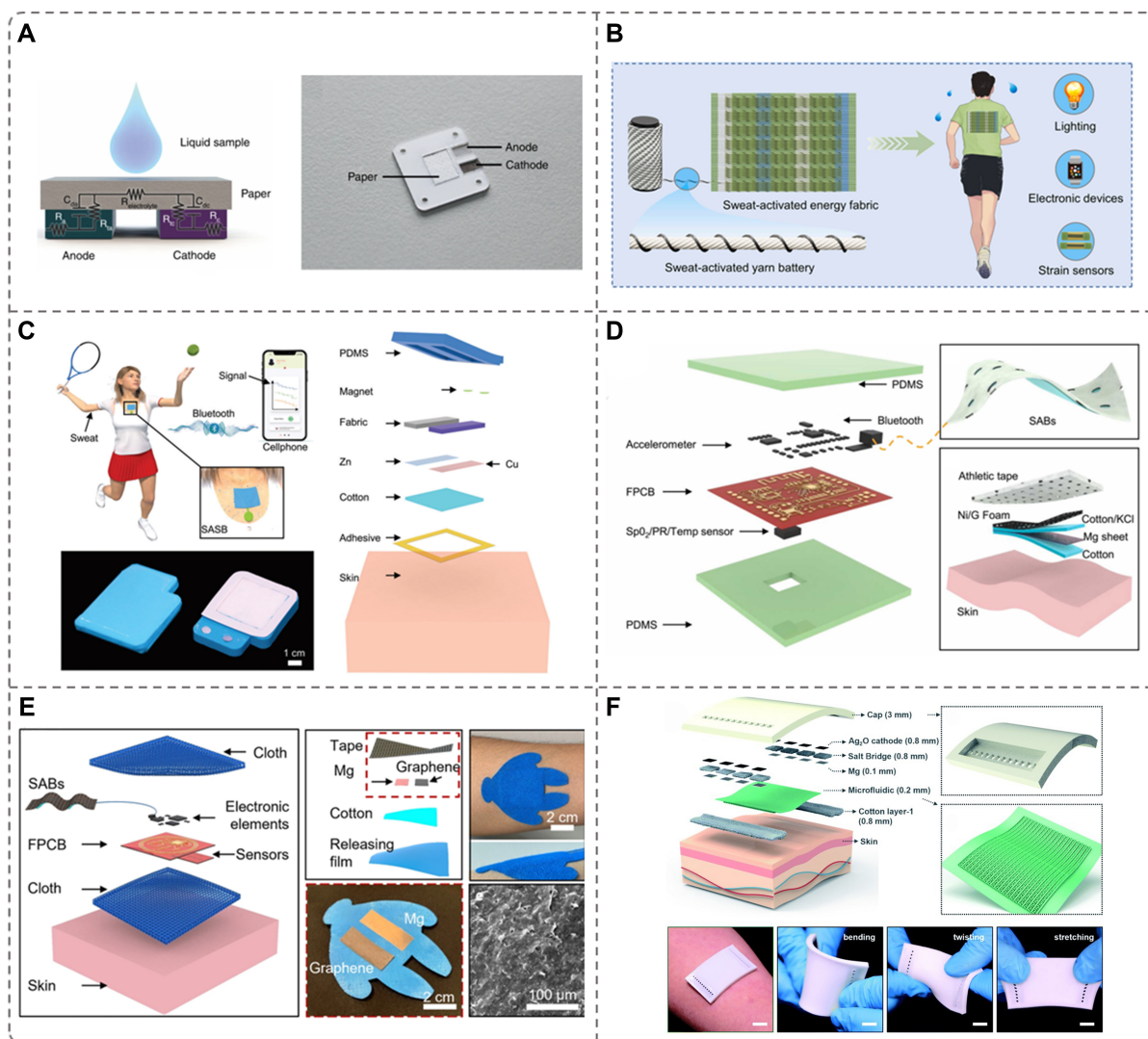


Figure 9. Sweat-activated batteries. (A) Self-powered smart patch for sweat conductivity monitoring. Reproduced under the terms and conditions of the CC BY^[145]. Copyright 2019, Author(s), published by Springer Nature; (B) Yarn-shaped batteries activated by an ultralow volume of sweat for self-powered sensing textiles. Reproduced with permission^[146]. Copyright 2023, Elsevier; (C) Stretchable sweat-activated battery applied in skin electronics. Reproduced with permission^[147]. Copyright 2022, The Authors. *Advanced Science* published by Wiley VCH GmbH; (D) Bandage-based energy generators activated by sweat. Reproduced with permission^[148]. Copyright 2022, Elsevier; (E) Sweat-activated batteries embedded within garment. Reproduced under the terms and conditions of the CC BY^[69]. Copyright 2022, Author(s), published by Springer Nature; (F) Bio-inspired ultra-thin microfluidics for soft sweat-activated batteries. Scale bar: 5 mm. Reproduced with permission^[149]. Copyright 2022, Royal Society of Chemistry.

values under physiological status and locations of sweat sampling of different individuals, which have also been previously studied^[69,149,150]. Recently, in order to improve the power performance and stability of sweat-based energy harvesters during operation, a series of research and developments have been proposed, for example, integrating the BFC with energy management components, integrating BFC with biomechanical energy harvesting systems, and so on^[156-158].

SWEAT-BASED PLATFORM DATA DISPLAY METHODS

Wearable technology has sparked interest in personal health monitoring, particularly sweat sensors that provide insights into physiological state. These sensors measure electrolyte levels, metabolites, and

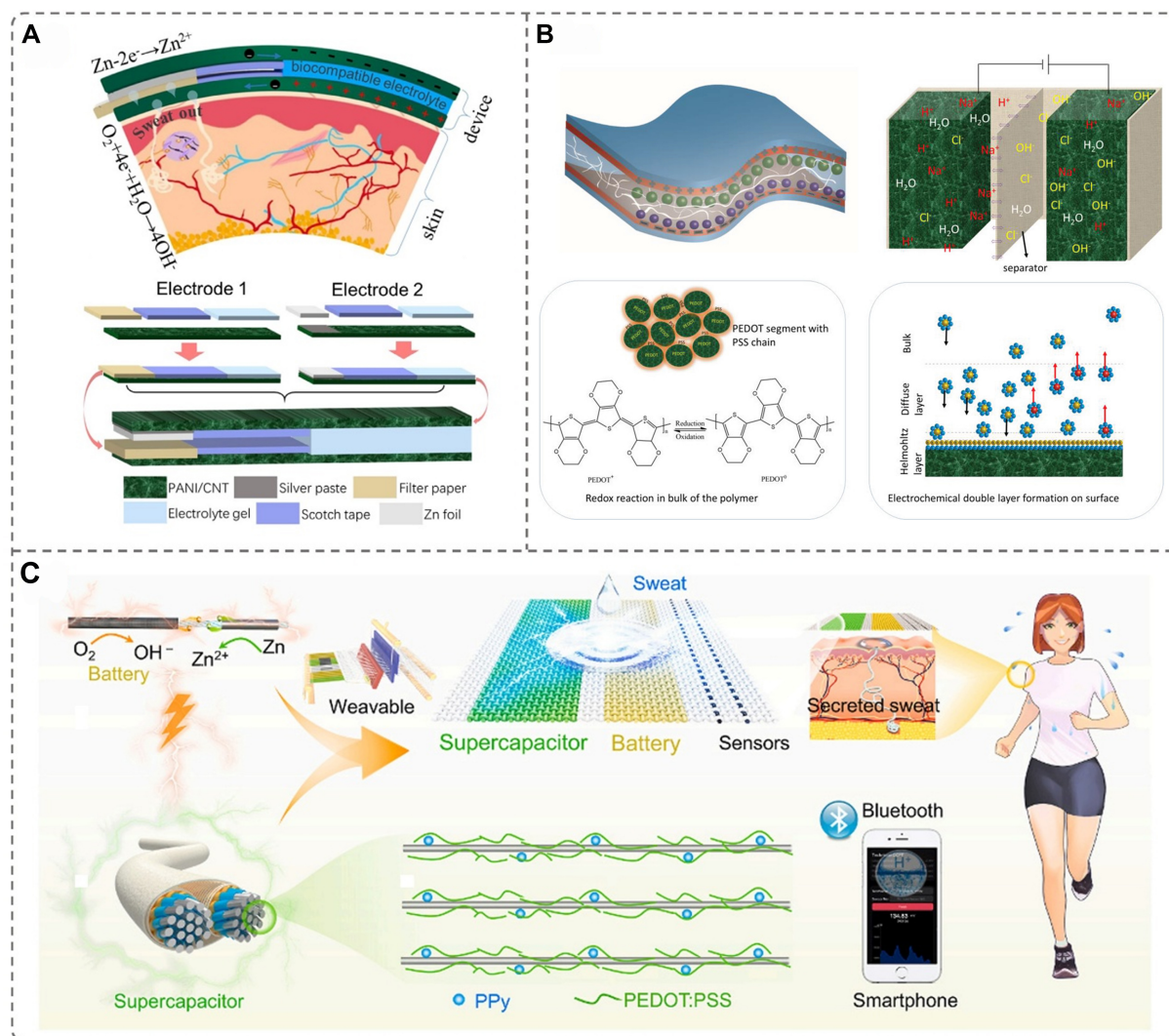


Figure 10. Sweat-activated supercapacitors. (A) Sweat-chargeable on-skin supercapacitors. Reproduced with permission^[153]. Copyright 2021, Elsevier; (B) Fabric-Based Wearable Supercapacitor Utilizing PEDOT:PSS-Coated Cloth and Sweat as Electrolyte. Reproduced under the terms and conditions of the CC BY^[154]. Copyright 2020, Author(s), published by WILEY VCH Verlag GmbH & Co. KGaA, Weinheim; (C) Weavable yarn-shaped supercapacitor for wireless sweat biosensing. Reproduced with permission^[37]. Copyright 2023, Elsevier. PEDOT:PSS: Polypyrrole/poly (3,4-ethylenedioxythiophene):poly (styrenesulfonate).

hydration in sweat. However, effectively conveying this data to users has been challenging. To address this, researchers explore innovative data display methods for sweat sensors, especially in mobile phone displays. These displays offer a convenient and accessible platform for users to interact with sweat-related data. Incorporating elements, such as color, LEDs, actuators, and sound, enhances the user experience and provides valuable health insights. These advancements have the potential to revolutionize how we monitor and understand our well-being.

Huang *et al.* developed a SAB embedded in wearable electronics, enabling real-time sweat monitoring. The sensor patch converts signals to digital format using 12-bit analog-to-digital converters (ADCs) and stores them in a two-megabit electrically erasable programmable read-only memory (EEPROM). When the phone is nearby, the NFC chip triggers the microcontroller (MCU) to read the data from the EEPROM via I2C and transfers it to the phone for display and storage in the app [Figure 12A]^[69]. Bandodkar *et al.* presented a

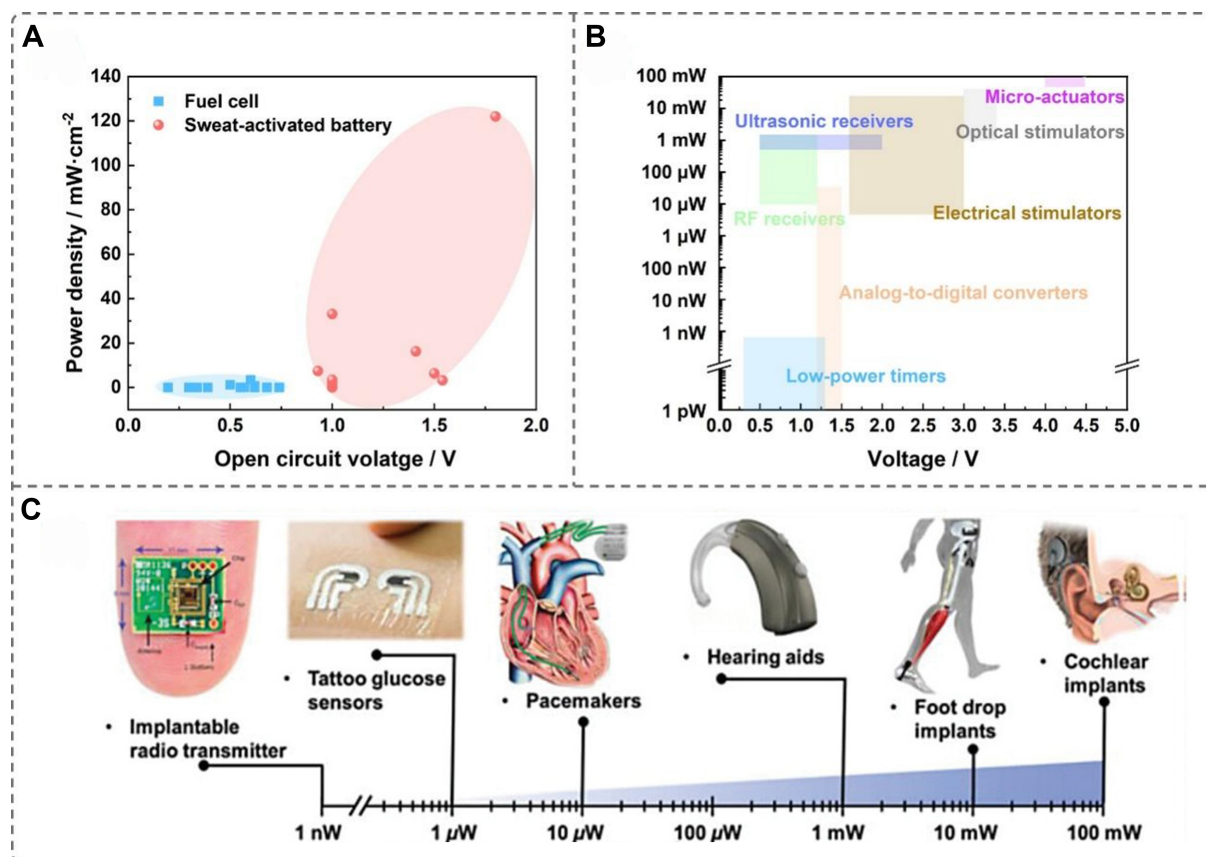


Figure 11. Typical power requirements for wearable devices. (A) Development of OCP and power density in BFCs and SABs; (B) Power consumption and voltage requirements of electronic modules in flexible electronics; (C) Power density considerations for viability of bioelectronics systems. Reproduced with permission^[155]. Copyright 2021, Wiley-VCH. OCP: Open-circuit potential; BFCs: biofuel cells; SABs: sweat-activated batteries.

native, battery-free electronic sensing system that draws inspiration from BFCs. This system combines chronometric microfluidic platforms with embedded colorimetric assays. By leveraging NFC technology in smartphones, wireless data extraction is achieved, and the smartphone camera captures digital images for colorimetric analysis. This enables visual interpretation and quantification of sweat rate/loss, pH, and chloride [Figure 12B]^[60]. Additionally, LEDs prove effective in real-time visualization of health status. Zhao *et al.* have created a system called the Health Status Sensing and Visualization System (HSSVS) that leverages color changes in LEDs to easily identify fluctuations in health status [Figure 12C]^[150]. In addition to visual displays of health fluctuations, touch serves as a significant reminder of our health status, offering distinct and valuable insights into our bodies and well-being. Recently, Huang *et al.* presented a sweat monitoring system that analyzes multiple components in fresh sweat (NH_4^+ , pH, Na^+ , skin impedance, glucose, and surface temperature) during exercise. Furthermore, the researchers introduced a groundbreaking safety warning mechanism as an integral system part. This mechanism utilizes a compact actuator to deliver mechanical stimuli, working in conjunction with six distinct color LEDs. Each LED corresponds to one of the six biosensors, ensuring users receive simultaneous safety alerts [Figure 12D]^[159].

CONCLUSION AND OUTLOOK

In the preceding sections, we have discussed various sweat sampling methods, sweat sensors, sweat-based energy harvesters, and sweat data display methods. Although numerous studies have been conducted at the

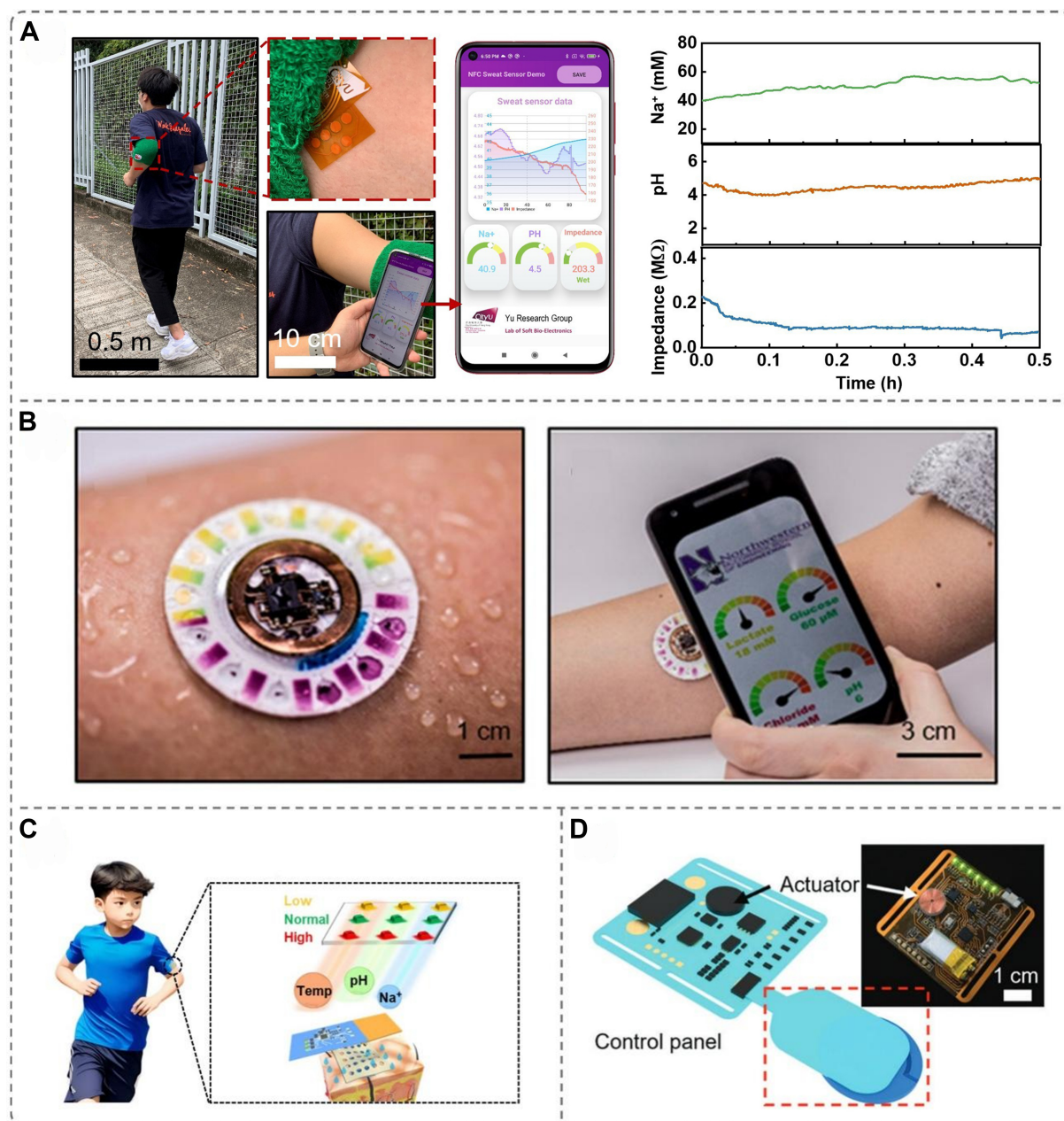


Figure 12. Sweat-based platform data display methods. (A) Mobile phone display for sweat sensor data. Reproduced under the terms and conditions of the CC BY^[69]. Copyright 2022, Author(s), published by Springer Nature; (B) Colorimetric assays in chronometric microfluidic platforms for sweat sensing. Reproduced under the terms and conditions of the CC BY-NC^[60]. Copyright 2022, Author(s), published by The American Association for the Advancement of Science; (C) LED-based health status sensing and visualization system. Reproduced under the terms and conditions of the CC BY^[50]. Copyright 2023, Author(s), published by Wiley VCH GmbH; (D) Skin-integrated sweat monitor with mechanical stimulus and LED safety warning. Reproduced with permission^[59]. Copyright 2021, Wiley-VCH. LED: Light-emitting diode.

device level (including sensors, powering systems, and electronic components), ensuring an adequate sweat supply, highly sensitive sensors with low energy consumption still pose significant challenges.

From the sweat sampling methods, enabling sweat secretion in sedentary environments is crucial for expanding their applications beyond sports-related scenarios. However, iontophoresis, while showing

promise for one-time measurements, may cause skin irritation or discomfort, making it less suitable for individuals with sensitive skin or conditions such as dermatitis. More new techniques need to be explored for sweat sampling. For example, to enhance the sweat extract ability, further in-depth research on the human sweating mechanism is necessary, along with developing corresponding database models specific to different populations. This will enable efficient and personalized sweat collection. Additionally, enhancing the collection capabilities of microfluidics, improving anti-interference abilities, and reducing water evaporation are vital in ensuring thorough and adequate sweat collection.

From the perspective of wearable sweat sensors, significant progress has been made in correlating physiological biomarkers with diseases. However, additional investigation is required to merge multiple sensing modalities into a singular device capable of simultaneously detecting multiple analytes. As for these sensors, it is crucial to evaluate wearable sensors by detecting a wide range of populations, including various moods, age groups, genders, geographical locations, and so on. This can offer a more holistic view of an individual's physiological condition. Additionally, current electrochemical biosensors relying on enzymes require more investigations into stability and environmental tolerance. The introduction of non-enzymatic sensors could directly detect target analytes in sweat using nanomaterials, eliminating the need for enzymes, which offer advantages including improved stability, longer shelf life, and reduced cost. Optical sweat sensors are an emerging field of research in sweat sensor technology. These sensors utilize light-based techniques, such as fluorescence or absorbance spectroscopy, to detect and analyze biomarkers in sweat. They offer advantages such as noninvasiveness, real-time monitoring, and high sensitivity. Ongoing research aims to improve the performance of optical sweat sensors by exploring advanced photonic materials, miniaturized sensor designs, and signal processing algorithms.

To enhance the suitability of sweat-based bioelectronic systems for energy storage, it is crucial to carefully consider the stability of electrodes due to the complex composition of sweat, which can lead to corrosion and fouling. We should optimize the electrolyte composition and concentration to facilitate efficient ion transport while minimizing interference from sweat components. Investigating water retention within the systems is essential for the long-term functionality of sweat energy storage devices. Additionally, an efficient energy management system can maximize power utilization and stability.

From the data display perspective, real-time monitoring and transmission of human sweat marker fluctuations enable the visualization and early warning of health status through visual and tactile data display methods. Advances in artificial intelligence algorithms facilitate health modeling and evaluation based on existing data, enhancing our understanding of health conditions.

The application field of the practical device also determines the degree of emphasis on different challenges in sweat electronics. For instance, in certain applications of sweat biomarkers monitoring, the device may prioritize the sweat sampling and sensing performance, while the sweat-based energy harvester may have more requirements in terms of electropower performance and biocompatibility. The data display has more potential for health visualization and early warning of human status. All in all, the challenges and opportunities in healthcare drive the advancement of flexible sweat sensors. Personalized data from these wearables is crucial for precise medical practices, encouraging active engagement in health management. Integrating consumer wearables with medical devices creates a connected network, providing comprehensive insights for researchers and clinicians. The seamless incorporation of sweat sensors into everyday routines augments the precision of personalized medicine.

DECLARATIONS

Authors' contributions

Initiated the reviewing idea and outlined the manuscript structure: Zhao G, Liu Y, Yu X

Conducted the literature review and wrote the manuscript: Zhao G, Li Z

Involved in the discussion and revised the manuscript: Huang X, Zhang Q

Supervision, review and editing, project administration: Yu X

Availability of data and materials

Not applicable.

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Conflicts of interest

Yu X is an Editorial Board Member of the journal *Soft Science*, while the other authors have declared that they have no conflicts of interest.

Ethical approval and consent to participate

Figures 3A, 3C, 3D, 4A, 4E, 5B, 5D, 6B, 6F, 7A, 7C, 7E, 7F, 8E, 9E, 9F, 12A and 12B are cited from the researches in refs^[16,47,49,52,54,55,60-62,69,76,104,108,111,139,149] respectively. The citations include images that depict specific body parts of the participants in the experiment, aiming to present the research results and experimental methods in a more intuitive manner. Strict measures have been taken during the production of these illustrations to ensure the privacy of the participants is safeguarded. The original images have undergone rigorous review to uphold privacy standards.

Consent for publication

Not applicable.

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