

## **IoMT-Based Wearable Sweat Sensors: A Systematic Review of Non-Invasive Biomarker Monitoring for the Management of Metabolic Diseases**

**Nayla Canthyka Yuni<sup>1\*</sup>, Aulia Umi Rohmatika<sup>2</sup>**

<sup>1</sup> Faculty of Medicine, Universitas Pembangunan Nasional Veteran Jawa Timur, East Java, Indonesia

### **Corresponding Author**

Nayla Canthyka Yuni<sup>1</sup>

Faculty of Medicine, Universitas Pembangunan Nasional Veteran Jawa Timur, East Java, Indonesia

Jl. Rungkut Madya, Gn. Anyar, Kec. Gn. Anyar, Surabaya, Jawa Timur 60294

082340911737

naylacanthyka@gmail.com

### **ABSTRACT**

Metabolic diseases such as type 2 diabetes mellitus, obesity, and metabolic syndrome continue to represent a growing global health burden. Conventional invasive monitoring methods often cause discomfort, repeated skin injury, and increased risk of infection, thereby encouraging the development of non-invasive monitoring technologies based on the Internet of Medical Things (IoMT). This systematic literature review aimed to synthesize recent advances in IoMT-based wearable sweat sensors as non-invasive biomarker monitoring platforms for metabolic disease management. A systematic literature search was conducted in PubMed and Google Scholar for articles published between 2021 and 2026 using keywords related to wearable sensors, sweat biomarkers, IoMT, and metabolic diseases. Following eligibility screening, 36 studies were included and analyzed. The findings revealed rapid advancements in wearable sweat-sensing technologies, particularly electrochemical, colorimetric, and microfluidic platforms integrated with IoMT architectures. Major biomarkers monitored through glucose, lactate, cortisol, and inflammatory cytokines such as IL-6 and TNF- $\alpha$ . Several studies demonstrated strong correlations between sweat biomarkers and conventional clinical measurements, while IoMT architectures integrated with Bluetooth Low Energy (BLE) and machine learning enabled accurate real-time monitoring. Overall, IoMT-based wearable sweat sensors demonstrate considerable potential as non-invasive tools for continuous metabolic disease monitoring and management. Nevertheless, challenges related to clinical validation, sensor stability, standardization, and data security must be addressed before widespread clinical adoption.

**Keywords :** IoMT; Wearable biosensors; Sweat biomarkers; Metabolic disease; Non-invasive monitoring; Digital health.

## Introduction

Metabolic diseases, including type 2 diabetes mellitus (T2DM), obesity, metabolic syndrome, and non-alcoholic fatty liver disease (NAFLD/NASH), have become major global health problems with continuously increasing prevalence worldwide<sup>1</sup>. These diseases contribute significantly to morbidity, mortality, and healthcare costs due to long-term complications and the need for continuous metabolic monitoring<sup>2</sup>. Conventional diagnostic and monitoring approaches still predominantly rely on invasive blood sampling, which may cause discomfort, repeated skin injury, risk of infection, and limited capability for continuous real-time monitoring in daily clinical practice<sup>3</sup>.

Recent advances in wearable biosensing technologies have encouraged the development of non-invasive monitoring systems using alternative biofluids<sup>4</sup>. Among various biofluids such as saliva, tears, and interstitial fluid (ISF), sweat has emerged as one of the most promising candidates because it can be collected non-invasively, continuously secreted, and contains clinically relevant biomarkers<sup>1</sup>. Human sweat contains a wide range of biomarkers, including glucose, lactate, urea, sodium, potassium, chloride, cortisol, and inflammatory cytokines such as interleukin-6 (IL-6) and tumor necrosis factor-alpha (TNF- $\alpha$ ). These biomarkers provide valuable physiological and metabolic information for disease monitoring and personalized healthcare applications<sup>2</sup>. Several of these biomarkers have demonstrated significant correlations with blood-derived physiological parameters, supporting their potential use as surrogate indicators for assessing metabolic status, disease progression, and therapeutic responses in patients with metabolic disorder.

The rapid development of nanotechnology, flexible electronics, microfluidic systems, and miniaturized biosensors has accelerated the emergence of wearable sweat sensors capable of real-time biochemical monitoring directly on the skin surface<sup>5</sup>. These wearable platforms utilize electrochemical, colorimetric, fluorescence, and multimodal sensing technologies integrated into flexible and portable devices. Furthermore, the integration of wearable sweat sensors with the Internet of Medical Things (IoMT) enables wireless data transmission, cloud-based analysis, machine learning-assisted interpretation, and remote healthcare monitoring through smartphone-connected systems<sup>6</sup>.

Despite their significant potential, wearable sweat biosensors still face several technical and clinical challenges<sup>7</sup>. Variability in sweat production rates, environmental interference, biofouling, limited long-term stability, calibration difficulties, and lack of standardized sweat biomarker references remain major barriers to clinical implementation<sup>8-10</sup>. In addition, concerns regarding patient privacy, cybersecurity, and ethical management of continuous biometric data have become increasingly important in the era of digital healthcare<sup>11</sup>.

Although numerous reviews have discussed wearable biosensors, flexible electronics, and sweat-based sensing technologies, most have primarily focused on sensor design, fabrication strategies, analytical performance, or individual biomarker detection<sup>8,12</sup>. Comprehensive evaluations that specifically address the integration of wearable sweat sensors with Internet of Medical Things

(IoMT) infrastructures, artificial intelligence (AI)-assisted data analytics, and their applications in metabolic disease management remain relatively limited<sup>13-15</sup>. Moreover, rapid technological advancements in sensor materials, wireless communication systems, cloud computing, and machine learning algorithms over the past few years have substantially expanded the capabilities of wearable sweat sensing platforms, necessitating an updated synthesis of the current evidence.

Given the growing demand for personalized, preventive, and remote healthcare solutions, understanding the technological readiness, clinical utility, and implementation challenges of IoMT-based wearable sweat sensor is increasingly important. A comprehensive assessment of recent developments can provide valuable insights for researchers, clinicians, biomedical engineers, and healthcare policymakers seeking to facilitate the translation of these technologies from experimental settings into routine clinical practice and future digital healthcare ecosystems.

Therefore, this literature review aims to critically synthesize recent advances in IoMT-based wearable sweat sensors published between 2021 and 2026, focusing on sensing technologies, sweat biomarkers, IoMT integration, artificial intelligence applications, clinical relevance in metabolic disease management, and current limitations toward future implementation in personalized and non-invasive healthcare systems.

## **Material and Methods**

This study was conducted using a Systematic Narrative Review design to summarize and synthesize recent developments in IoMT-based wearable sweat sensor technologies for metabolic disease management. The review protocol was designed to ensure that the selected literature was clinically relevant, scientifically valid, and technologically up to date. Literature searching was performed systematically using PubMed and Google Scholar databases. The search was limited to articles published between 2021 and 2026 to capture recent innovations in wearable biosensors and Internet of Medical Things (IoMT) applications.

The search strategy utilized Boolean operators (AND, OR) with several combinations of keywords, including "wearable sweat sensor", "sweat biomarker", "IoMT", "real-time monitoring", "non-invasive monitoring", "diabetes", and "metabolic syndrome". Articles included in this review consisted of studies discussing wearable sweat biosensors, digital integration or IoMT systems, and biomarker monitoring related to metabolic diseases. Only full-text articles published in English or Indonesian were included. Conference proceedings without peer review, incomplete articles, and studies focusing exclusively on non-sweat biofluids without wearable relevance were excluded from the analysis.

The initial screening process was conducted based on titles and abstracts, followed by full-text evaluation to determine eligibility. A total of 36 articles were finally selected for qualitative synthesis, consisting of systematic reviews, narrative reviews, comprehensive reviews, research articles, and observational studies related to wearable sweat biosensors and IoMT-based healthcare

technologies.

Data extracted from the selected studies included sensor technology, biomarker type, wearable platform, IoMT integration system, sensing methods, clinical applications, and study outcomes. The collected data were analyzed thematically and categorized into three major themes: development of wearable sensor materials and sensing mechanisms, integration of IoMT and wireless healthcare systems, and clinical applications for metabolic disease monitoring. Comparative analysis between studies was conducted to identify technological trends, clinical relevance, advantages, limitations, and future challenges in the implementation of wearable sweat biosensors for personalized healthcare systems.

**Tabel 1. Literature Review: Wearable Sweat Biosensor untuk Monitoring Biomarker Kesehatan**

No	Author, Country, Study Design	Characteristic of Participants	Information of Study	Result	Description of Result
1	Yin X et al., 2025; Netherlands; Observational clinical study and kinetic modeling	50 patients undergoing aortic valve replacement (AVR), 44 analyzed; majority male (82%); median age 73 years.	Developed a method for estimating blood cortisol levels using non-invasive sweat sensors based on kinetic modeling of cortisol transport from blood to sweat. The model covers physiological mechanisms: free cortisol, diffusion, convection, and 11beta-HSD2 enzyme activity.	Pearson correlation $r = 0.95$ (95% CI: 0.92–0.97), RMSE 65 nmol/L between estimated blood cortisol and actual results.	Wearable sweat sensors demonstrate high potential for non-invasive and continuous cortisol monitoring. Applicable in metabolic disorders, chronic stress, Cushing syndrome, and postoperative patients. Kinetic modeling improves accuracy compared to conventional linear regression.
2	Ibrahim NFA et al., 2022; Malaysia; Comprehensive review study	No direct participants (review article).	Reviewed the latest developments in wearable sweat-sensing devices (SSDs) for non-invasive and real-time biomarker monitoring. Covers continuous-flow and non-continuous-flow sweat analysis, sensor mechanisms, microfluidic systems, and wearable biosensor design.	Sweat contains important biomarkers: glucose, lactate, cortisol, electrolytes, uric acid, dopamine, and heavy metals, detectable using wearable sensors.	Wearable sweat sensors have great potential as a non-invasive monitoring platform. Microfluidic devices improve analysis accuracy. Challenges: sensor stability, sweat flow continuity, long-term comfort, and electronic integration.
3	Dong W & Chen X., 2025; China; Review article	No direct subjects (review article).	Reviewed wearable electrochemical biosensors based on metal-organic frameworks (MOFs) for sweat biomarker detection. Covers sensitive materials, detection principles, biomarkers (glucose, lactate, cortisol), MOF fabrication methods, and hydrogel integration.	MOF materials have advantages: high porosity, good sensitivity, large surface area, and improved biosensor selectivity and performance.	MOF-based wearable sweat sensors have the potential to become the next generation of non-invasive biosensors. Integration of MOFs with hydrogels and conductive materials enhances sensitivity and comfort. Challenges: anti-interference capability, clinical standardization, and medical validation.
4	Zhu Q et al., 2024;	No direct	Reviewed biomaterial-	BM-TENGs can	BM-TENGs are

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	China; Review article	participants (review article).	based triboelectric nanogenerators (BM-TENGs) as self-powered wearable and implantable devices. Covers TENG working principles, biomaterials, hydrogels, wearable monitoring, biosensing, and IoT integration.	convert biomechanical energy (movement, pulse, respiration, muscle activity) into electrical energy to support wearable biosensors.	flexible, biodegradable, biocompatible, and support non-invasive real-time monitoring. Challenges: performance optimization, device stability, and long-term clinical integration.
5	Wang H & Wu W., 2025; China; Review article	No direct subjects (review article).	Reviewed the development of microfluidic biosensors in point-of-care testing (POCT) and clinical applications. Covers detection of nucleic acids, proteins, metabolites, pathogens, and wearable and implantable biosensors.	Combination of microfluidic chips and high-sensitivity biosensors enables rapid, accurate, miniaturized, and portable biomarker detection for real-time monitoring.	Microfluidic biosensors have great potential in developing wearable sweat biosensors and point-of-care diagnostics. Challenges: clinical standardization, signal stability, biological interference, and device integration.
6	Rao LT, Mandal CK, & Patolsky F., 2025; Israel; Review article	No direct participants (review article).	Discussed body fluid-based diagnostic technologies (sweat, saliva, urine, tears, ISF) for POCT. Focus on wearable biosensors, microneedle-based sensing, continuous monitoring, AI/ML integration, and personalized healthcare.	Sweat excels as a non-invasive biofluid that is easy to collect, but has biomarker variability and lower correlation to plasma. Interstitial fluid (ISF) is considered more stable.	Sweat-based wearable biosensors are highly potential for real-time monitoring, fitness tracking, hydration, and stress monitoring. For high-precision clinical applications, microneedle-based ISF technology is predicted to be the future. AI/ML integration will accelerate predictive healthcare.
7	Du Z et al., 2026; China; Systematic Review	No direct participants (systematic review).	Reviewed wearable sweat sensors for detecting biomarkers: electrolytes, metabolites, hormones, neuromarkers, and pharmaceutical compounds. Covers sweat absorption unit, sensing unit, signal processing, microfluidics, and wireless transmission technology.	Flexible electronics, microfluidics, and wearable biosensing enable real-time, non-invasive, portable, and continuous biomarker monitoring with multi-biomarker detection capability.	Wearable sweat sensors have great prospects in healthcare monitoring, athlete monitoring, industrial safety, and early disease detection. AI-based signal processing and wireless communication integration are the main development directions.
8	Qiao Y et al., 2022; China & USA; Review Article	No direct participants (review).	Discussed wearable sweat sensors for continuous and non-invasive biomarker monitoring: glucose, lactate, electrolytes, pH, cortisol, vitamins, ethanol, and drugs. Covers patch, tattoo, textile, paper-based, and glasses-integrated sensor platforms.	Sweat contains important biomarkers for monitoring diabetes, dehydration, fatigue, stress, and chronic diseases. Wearable sensing enables real-time monitoring without invasive procedures.	Wearable sweat biosensors have great potential in personalized healthcare and preventive medicine. Challenges: sweat collection stability, air permeability, biocompatibility, power consumption, and real-time wireless data transmission.

No	Author, Country, Study Design	Characteristic of Participants	Information of Study	Result	Description of Result
9	Yuan X et al., 2023; China; Review Article	No direct participants (review).	Discussed epidermal wearable biosensors for chronic disease biomarker monitoring through sweat. Covers sweat extraction methods, electrochemical sensing, and biomarkers in diabetes, cystic fibrosis, epilepsy, schizophrenia, and chronic inflammatory diseases.	Sweat biomarkers correlate closely with various chronic diseases. Sweat chloride is the gold standard for cystic fibrosis diagnosis; sweat glucose has potential for non-invasive diabetes monitoring.	Epidermal wearable biosensors have great prospects for personalized healthcare and early disease detection. Integration of IoT, big data, and wireless monitoring is predicted to be the future of healthcare systems. Challenges: clinical validation, sweat-blood biomarker correlation, and sensor stability.
10	Alves TMR et al., 2021; Brazil; Review Article	No direct participants (review).	Discussed wireless wearable electrochemical sensors based on IoT for real-time biomarker monitoring. Covers electrochemical sensing methods, wireless communication protocols (Bluetooth, NFC, RFID, ZigBee), flexible electronics, and power source systems.	Electrochemical wearable sensors have advantages of miniaturization, flexibility, high sensitivity, low power consumption, and continuous real-time monitoring. Sweat is the most potential biofluid.	Integration of wearable electrochemical sensors with IoT and wireless communication is the foundation of future personalized healthcare. Challenges: calibration stability, biofouling, sensitivity, selectivity, long-term stability, and power management.
11	Luo TT et al., 2021; China; Review Article	No direct participants (review).	Discussed sweat lactate monitoring as a non-invasive method for assessing physiological conditions, energy metabolism, exercise physiology, tissue ischemia, and health surveillance. Covers sweat collection, lactate detection methods, and wearable lactate biosensors.	Sweat lactate is an important biomarker for monitoring fatigue, anaerobic metabolism, tissue ischemia, pressure injury, and exercise physiology. Wearable sensors enable continuous and portable monitoring.	Wearable sweat lactate monitoring has prospects in sports medicine, intensive care, pressure ulcer prediction, and metabolic health. Challenges: sweat collection standardization, biomarker stability, and validation of sweat-blood relationship.
12	Yang P et al., 2022; China; Review Article	No direct participants (review).	Discussed wearable sweat sensors for long-term health monitoring: sweat collection, biosensing technologies, energy supply systems, self-powered devices, data transmission, and AI for intelligent monitoring. Biomarkers: sodium, chloride, potassium, glucose, lactate, cortisol.	Sweat is a highly potential non-invasive biofluid for continuous monitoring as it contains various metabolic and physiological biomarkers.	Main challenges: sweat collection efficiency, long-term stability, biocompatibility, energy management, and sensor durability. AI, microfluidics, self-powered systems, and wireless communication integration are the main development directions.
13	Guo WT et al., 2026; China; Review Article	No direct participants (review).	Discussed multimodal biosensing platforms integrating various sensing modalities (electrochemical, optical, microwave, gas, piezoelectric) with AI	Multimodal biosensors have enhanced sensitivity, specificity, robustness, real-time monitoring, and simultaneous multi-biomarker detection.	Sensor-computing integration is the future of intelligent healthcare. Development of flexible electronics, AI-driven processing, and multimodal sensing will

No	Author, Country, Study Design	Characteristic of Participants	Information of Study	Result	Description of Result
			and sensor-computing systems. Covers multimodal wearable biosensors for sweat biomarkers.	AI integration enables intelligent analysis and adaptive health monitoring.	accelerate personalized healthcare. Challenges: data harmonization, device scalability, and regulatory barriers.
14	Ghosh A et al., 2023; India; Review Article	No direct participants (review).	Discussed smart materials, soft electronics, nanotechnology, wearable biosensors, and AI in healthcare wearables. Covers wearable sweat sensors, temperature sensors, strain sensors, VOC sensors, electrochromic biosensors, and IoT-integrated systems.	Smart wearable devices enable real-time monitoring, non-invasive diagnosis, remote healthcare, and personalized medicine. Wearable sweat biosensors can detect glucose, lactate, sodium, pH, and volatile biomarkers.	Integration of smart materials, soft electronics, AI, IoT, and energy harvesting will improve user compliance and self-powered healthcare systems. Challenges: ergonomics, power supply, washability, durability, and long-term reliability.
15	Hua Z et al., 2025; China & Hong Kong; Review Article	No direct participants (review).	Discussed wearable bioelectronics for cancer diagnosis, prognostic monitoring, rehabilitation, and personalized medicine. Covers electrochemical and optical sensing, ultrasound imaging, microneedle biosensors, wearable patches, hydrogel systems, and AI-integrated devices.	Wearable bioelectronics have high sensitivity, continuous monitoring, minimally invasive detection, and multimodal sensing. Integration of IoMT, cloud-based analysis, and AI enables intelligent diagnostics.	Wearable bioelectronics are the future of intelligent theranostics and precision medicine. Development of AI-driven analysis and closed-loop monitoring will accelerate digital healthcare transformation. Challenges: device miniaturization and signal stability.
16	Akter A et al., 2024; Saudi Arabia, USA, India; Systematic Review	No direct participants (systematic review).	Reviewed wearable sweat sensors based on smart textiles for personal health monitoring. Focus on electrochemical sensors, biosensors, optical sensors, microfluidic sensors, ion-selective electrodes (ISEs), conductive polymers, and nanomaterials.	Smart textile-based sweat sensors can perform continuous, non-invasive, real-time monitoring of biomarkers: glucose, lactate, cortisol, sodium, potassium, pH, hydration, and electrolyte balance.	Wearable sweat sensors based on smart textiles have great potential in personalized medicine, sports medicine, and proactive healthcare. Challenges: durability, signal stability, sweat collection efficiency, washability, and long-term user comfort.
17	European Commission JRC, 2024; European Union; Horizon Scanning & Strategic Foresight Report	16 multidisciplinary experts in a horizon scanning workshop on medical imaging and AI.	Evaluated emerging technologies in medical imaging and AI: generative AI, digital twins, multimodal data analysis, explainable AI, AI-generated synthetic data, XR, wearable electronics, blockchain healthcare, and edge computing.	The future of healthcare will be dominated by AI, multimodal biosensing, digital twins, synthetic medical data, and explainable AI for personalized diagnostics and remote monitoring.	AI healthcare development requires data infrastructure, ethical frameworks, explainable AI, workforce adaptation, and trust-based healthcare ecosystems. Wearable electronics and AI-driven healthcare are predicted to be the core of future precision medicine.
18	Tamilselvi T et al., 2023; India; System Design & Literature-Based Research	Focus on elderly population with physical limitations,	Developed a concept of IoT and deep learning-based wearable sweat sensor for real-time	Integration of wearable sweat sensor, IoT, cloud computing, and deep learning	IoT-based wearable sweat sensor has great potential in AAL, remote patient

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		degenerative diseases, diabetes, and cardiovascular disorders in the Ambient Assisted Living (AAL) concept.	elderly health monitoring. The system monitors heart rate, blood pressure, SpO <sub>2</sub> , blood glucose, respiration rate, sweat rate, uric acid, and body temperature.	improves accuracy of elderly health condition prediction compared to conventional monitoring models.	monitoring, and preventive healthcare. Advantages: real-time monitoring, low-cost, portable, context-aware, and supports independent living in the elderly population.
19	Madrigal-Cerezo R et al., 2026; Spain; Structured Narrative Review	Various studies on athletes, healthy adults, cyclists, soccer players, and swimmers in physiological, biomechanical, and biochemical monitoring.	Reviewed integration of wearable biosensing and machine learning for adaptive monitoring, intelligent coaching, precision medicine, and AI-driven healthcare. Focus on HRV sensors, sweat biosensors, EMG, IMU, multimodal biosensing, and digital twins.	Wearable biosensors can perform continuous monitoring of physiological, biomechanical, and biochemical biomarkers in real-time. Sweat lactate sensor shows strong correlation with blood lactate ( $r > 0.85$ ).	The future of wearable biosensing moves toward a multimodal AI-driven healthcare ecosystem with integration of digital twins, adaptive feedback systems, and explainable AI. Challenges: signal noise, motion artifacts, sensor drift, data privacy, and ethical AI governance.
20	Gupta SL & Basu S, 2022; India & USA; Book Chapter / Narrative Review	No specific participants (narrative review/conceptual discussion).	Discussed smart nanosensors for healthcare: wearable biosensors, electrochemical sensors, nanobiosensors, quantum dots, graphene-based sensors, carbon nanotubes, flexible nanosystems, and AI-integrated healthcare. Applications in blood, saliva, tears, sweat, and ISF.	Nanosensors have high sensitivity, rapid detection, miniaturization, portability, and continuous real-time monitoring capability. Wearable nanobiosensors can monitor glucose, lactate, electrolytes, and metabolites through sweat.	Nanosensors are the main foundation of future smart healthcare systems supporting personalized medicine, wearable monitoring, AI-based diagnostics, and IoMT. Future direction: wearable nanosensors, smart implantable devices, nanorobotics, and continuous biosignal monitoring.
21	Ibrahim NFA et al., 2022; Malaysia; Comprehensive Review	No direct participants (comprehensive review).	Discussed wearable sweat-sensing devices including sweat biomarkers, electrochemical sensing, microfluidic systems, epidermal patch, sweatband, textile-based sensor, wireless monitoring, and continuous and non-continuous flow sweat analysis.	Sweat contains important biomarkers: glucose, lactate, uric acid, cortisol, electrolytes, dopamine, alcohol, nicotine, and heavy metals. Microfluidic systems improve sensing accuracy by minimizing mixing of fresh and old sweat.	Wearable sweat-sensing devices have great potential as future non-invasive healthcare platforms. Development focuses on flexible electronics, textile biosensors, microfluidic integration, sensor miniaturization, and AI-assisted biosensing platforms.
22	Zafar H et al., 2022; Serbia, Romania, Italy; Comprehensive Review	No specific participants (review of wearable sweat-glucose sensors).	Discussed wearable sweat-glucose sensing methods: electrochemical biosensor, enzymatic glucose detection, epidermal patch, tattoo biosensor, graphene-based flexible sensor, iontophoresis-assisted sensing, microfluidic sweat collection, and	Sweat glucose correlates with blood glucose (concentration ~100 times lower). Electrochemical sensing shows the greatest commercialization potential for diabetes monitoring.	Wearable sweat-glucose biosensors are strong candidates for future diabetes management systems because they are painless, non-invasive, wearable, and continuous. Challenges: low glucose concentration in sweat, sensor stability,

No	Author, Country, Study Design	Characteristic of Participants	Information of Study	Result	Description of Result
			wireless monitoring platform.		calibration accuracy, and commercialization readiness.
23	Chu SS et al., 2022; USA; Review Article	No specific participants (review on multiplexed biosensor platforms for metabolic syndrome).	Discussed metabolic syndrome as a multifactorial condition (obesity, hypertension, hyperglycemia, dyslipidemia, inflammation, insulin resistance). Reviewed metabolic biomarkers and electrochemical and optical biosensing platforms based on sweat, saliva, tears, breath, and urine.	Single-analyte biosensor is suboptimal for metabolic syndrome diagnosis. Multiplexed multi-analyte biosensors are needed to improve diagnostic accuracy and real-time monitoring.	The future of metabolic disorder monitoring depends on multiplexed wearable biosensors, multimodal biosensing platforms, and continuous IoMT-based monitoring. Simultaneous integration of various metabolic biomarkers can improve early diagnosis and personalized healthcare.
24	Lyzwinski L et al., 2023; Canada & Switzerland; Perspective Article	No specific participants (perspective article on sweat-based wearable technologies for metabolic syndrome).	Discussed wearable sweat-based technologies for metabolic syndrome monitoring using biomarkers: glucose, sodium, CRP, uric acid, and cortisol. Covers wearable electrochemical sensor, smart textile, smartwatch, wristband, wearable patch, and AI-integrated cloud monitoring.	Sweat contains important biomarkers for non-invasive metabolic syndrome assessment. Some sensors show high correlation with gold standard clinical measurements.	Sweat-based wearable technology has great potential as a future digital metabolic healthcare platform. Future direction: integrated multimarker sweat patch, AI-assisted metabolic monitoring, and IoMT-based precision medicine. Challenges: biofouling prevention, long-term stability, and clinical validation.
25	Bjorkenheim A et al., 2025; Sweden; Prospective Observational Study	18 STEMI patients post-PCI and 6 control patients. Majority male, mean age ~59 years. Sweat and plasma were collected during the acute phase and at 4–6 weeks follow-up.	Evaluated inflammatory biomarkers in sweat and plasma using high-throughput proteomic assay on 92 inflammatory biomarkers post-myocardial infarction. Biomarkers: IL-6, HGF, STAMBP, TNFSF10, TNFSF11, MCP-2, and other inflammatory cytokines.	Plasma is more sensitive than sweat in detecting inflammatory biomarker changes post-STEMI. STAMBP was found higher in STEMI patients compared to controls in sweat.	Sweat has potential as a medium for non-invasive inflammatory biomarker monitoring based on wearable platforms, although its sensitivity is still lower than plasma. The study reinforces the potential of wearable sweat biosensors for cardiovascular and metabolic disease monitoring.
26	Khor SM et al., 2022; Korea & Malaysia; Review Article	No specific participants (review on wearable sweat glucose biosensors for Type II Diabetes).	Discussed development of wearable sweat glucose biosensors for point-of-care monitoring of type II diabetes mellitus. Reviews electrochemical biosensor, colorimetric biosensor, microfluidic system, enzymatic glucose oxidase (GOx) sensor, non-enzymatic sensor, and AI-integrated monitoring	Sweat glucose biosensor has great potential as a non-invasive continuous glucose monitoring system. Enzymatic biosensor has high sensitivity but limited shelf-life; non-enzymatic biosensor is more stable but still has selectivity issues.	Future wearable sweat glucose biosensors must be a fully integrated autonomous platform including microfluidic system, flexible electronics, wireless communication, multiplex sensing, and AI-assisted IoMT-based monitoring.

No	Author, Country, Study Design	Characteristic of Participants	Information of Study	Result	Description of Result
			system.		
27	Arshad F et al., 2026; Saudi Arabia; Review Article	No specific participants (translational review on biosensors for early detection of MASH/NASH).	Discussed biosensors for early detection of NASH/MASH based on point-of-care diagnostics. Reviews electrochemical biosensors, optical biosensors, CRISPR/Cas biosensors, nanomaterial-based biosensors, microfluidic biosensors, and integration of AI, cloud-based monitoring, and IoMT.	Biosensors have great potential as rapid, minimally invasive, cost-effective, and point-of-care diagnostic platforms. Electrochemical biosensor is sensitive to ALT/AST; microfluidic biosensor supports multiplex detection.	The future of biosensors for metabolic disease management lies in integration of wearable biosensors, AI-assisted analysis, cloud healthcare, and telemedicine. Combination of biosensors and IoMT enables continuous real-time monitoring for early detection of chronic metabolic diseases.
28	Wu T & Liu G., 2025; China; Review Article	No specific participants (review on non-invasive wearable biosensors for inflammation monitoring).	Discussed wearable biosensors for monitoring inflammatory biomarkers: IL-1beta, IL-6, IL-8, TNF-alpha, IFN-gamma, CRP, IL-10, and TGF-beta. Reviews microneedle patches, flexible electronic skin, textile-based sensors, electrochemical biosensors, and wearable sweat sensors.	Sweat cytokines (IL-6, IL-8, TNF-alpha, CRP, IL-1beta) correlate with systemic inflammatory status. Flexible wearable biosensors enable continuous real-time inflammatory monitoring with high comfort.	Wearable inflammation biosensors are the future of IoMT-based chronic disease monitoring. Integration of flexible electronics, microneedle technology, and AI-assisted data processing will enable continuous inflammation monitoring for precision medicine.
29	Kirubha P., Sreejaa B.S., & Sulthana S.F., 2026; India; Tutorial Review	No specific participants (tutorial review on non-enzymatic sweat-based glucose sensors for CGM in diabetes mellitus).	Discussed non-enzymatic glucose sensors based on sweat as an alternative non-invasive continuous glucose monitoring (CGM). Reviews electrocatalytic glucose oxidation, transition metal-based catalysts, carbon nanomaterials (graphene, CNTs, MXene), and flexible electronics.	Sweat glucose concentration ranges from 10–200 microM and correlates with blood glucose trends. Non-enzymatic sensors have high stability, long operational lifetime, and sensitivity to micromolar/nanomolar levels.	The future of wearable glucose biosensors depends on integration of AI-based data processing, microfluidic sweat management, wireless communication, and multiparameter sensing for personalized diabetes management. Challenges: sweat-rate variability, calibration accuracy, and sensor fouling.
30	Ramasubramanya A. et al., 2025; United States; Research Article	43 healthy participants (20 female, 23 male); age groups <25, 25–40, and >40 years. Using wearable perspiration biosensing system for 48 hours.	Developed a wearable sweat biosensing platform (Sweat AWARE) for continuous monitoring of cortisol, melatonin, IL-6, and TNF-alpha using aptamer and antibody-functionalized ZnO sensors. Using CatBoost and XGBoost regression models for data analysis.	AUC >0.80 for cortisol, melatonin, IL-6, and TNF-alpha. Sensors detect cortisol 1–256 ng/mL, melatonin 0.2–72.9 pg/mL, IL-6 1–256 pg/mL, and TNF-alpha 0.1–200 pg/mL with 80–120% recovery rate.	Passive sweat biosensing can be used as a non-invasive personalized chronobiological monitoring system to detect stress physiology, inflammatory activation, metabolic dysregulation, and circadian disruption in real-time.
31	Cheng C., Ganguly	Testing on tissue-	Developed a wearable	Sensor can detect	Combination of sweat

No	Author, Country, Study Design	Characteristic of Participants	Information of Study	Result	Description of Result
	S., Li P., & Tang X., 2024; Canada; Experimental Research Article	mimicking phantom and human on-body testing during aerobic and anaerobic exercise using a wearable hypoxia monitoring device.	device for simultaneous non-invasive monitoring of sweat lactate and tissue oxygenation (StO <sub>2</sub> ). Using hydrogel-based colorimetric lactate biosensor, near-infrared (NIR) sensor, and 3D-printed enclosure.	lactate up to 100 mM with proportional colorimetric response. Device can differentiate aerobic and anaerobic conditions based on increased sweat lactate and decreased oxygenation.	lactate monitoring and tissue oxygenation sensing provides a new approach for hypoxia detection, exercise physiology monitoring, sepsis detection, and athletic performance monitoring based on non-invasive multimodal biosensing.
32	Xian X., 2026; United States; Editorial Review	Editorial article reviewing various wearable biosensor studies for human health monitoring.	Discussed wearable biosensors in the healthcare transition toward point-of-care and home-care systems. Reviews sensing on sweat, tears, ISF, breath biomarkers, transcutaneous gas, heart rate, blood pressure, ECG, and body temperature monitoring.	Wearable biosensors are rapidly developing for continuous real-time health monitoring. Nanomaterials (graphene, CNTs, silver nanowires, MOF) improve sensor sensitivity, conductivity, miniaturization, and flexibility.	The future of wearable biosensors depends on integration of AI, IoT, wireless systems, nanomaterials, and additive manufacturing for personalized healthcare ecosystems. Challenges: miniaturization, long-term stability, sensor accuracy, and large-scale clinical adoption.
33	Assalve G. et al., 2024; Italy; Comprehensive Review	Reviewing studies on healthy athletes, cyclists, runners, kayakers, and various physical exercises indoors and outdoors.	Discussed wearable sweat biosensors for real-time monitoring of glucose, lactate, electrolytes, pH, and cortisol. Technologies include electrochemical sensing, colorimetric sensing, microfluidics, epidermal patch, tattoo sensor, paper-based sensor, and fabric-based sensor.	Lactate is used to determine anaerobic threshold and fatigue assessment. Electrochemical sensors show higher sensitivity and precision than colorimetric sensors, although colorimetric is cheaper with smartphone-based detection.	Wearable sweat biosensors have great potential for personalized sports medicine and precision athletic monitoring. Challenges: enzyme stability, environmental interference, sweat contamination, and standardization. Integration of AI, wireless transmission, and flexible electronics is the future of biosensing.
34	Pour S.R.S. et al., 2024; Italy; Review Article	No specific participants (review on wearable sweat biosensors based on microfluidic systems).	Discussed wearable biosensors based on sweat analysis using microfluidic technologies, paper-based microfluidics (PADs), electrochemical assay, colorimetric assay, enzymatic assay, immunoassay, and wireless communication. Biomarkers: glucose, lactate, urea, cortisol, electrolytes, hormones, and cytokines.	Microfluidic systems improve sweat sampling accuracy by reducing evaporation, contamination, and environmental interference. Paper-based microfluidic devices have advantages of low-cost, flexible, and multiplex detection.	Wearable sweat biosensors based on microfluidic technology are an important foundation for future personalized healthcare. Challenges: validation of sweat-blood biomarker correlation, sampling standardization, quantitative accuracy, and miniaturization.
35	Yang M. et al., 2024; China; Comprehensive Review	No specific participants (review on non-electrochemical	Discussed non-electrochemical sweat sensing methods: colorimetric methods, fluorescence, SERS,	Non-electrochemical sweat sensors have advantages: low power consumption, lightweight, low cost,	Non-electrochemical sweat biosensors have great potential for future wearable healthcare systems as they are

No	Author, Country, Study Design	Characteristic of Participants	Information of Study	Result	Description of Result
		sweat sensing).	paper-based microfluidics, thread-based microfluidics, and microfluidic valve systems. Biomarkers: glucose, lactate, chloride, sodium, calcium, pH, ammonia, ethanol, and other metabolites.	high comfortability, and do not require complex electronic systems. Colorimetric sensing enables smartphone-based monitoring.	simpler, cheaper, and more comfortable. Challenges: environmental interference, signal calibration, quantitative accuracy, and sweat analysis standardization.
36	Lin X., 2025; China; Review Article	No specific participants (review on wearable electrochemical sweat sensors).	Discussed wearable electrochemical biosensors for monitoring glucose, lactate, pH, sodium ions, chloride ions, and other sweat biomarkers. Technologies: flexible electrochemical arrays, hydrogel patch, graphene-gold mesh electrodes, MOF-based biosensors, conductive polymer hydrogels, and tattoo sensors.	Sweat glucose correlates with blood glucose; sweat lactate correlates significantly with blood lactate during high-intensity exercise. Sodium and chloride sweat sensing has potential for hydration monitoring and cystic fibrosis diagnosis.	Wearable electrochemical sweat sensors will play an important role in personalized medicine, smart healthcare, and sports physiology. Challenges: sensor stability, selectivity, biofouling, environmental calibration, and mass production scalability.

## Results

This section presents the main findings obtained from the reviewed studies regarding wearable sweat sensing technologies and their integration into Internet of Medical Things (IoMT) systems. The reviewed studies identified electrochemical and colorimetric sensors as the dominant technologies in wearable sweat sensing development. Electrochemical sensors demonstrated high sensitivity, specificity, and analytical accuracy, particularly through the integration of nanomaterials such as MOFs, MXene, graphene, and carbon nanotubes. In contrast, colorimetric sensors offered lower production costs, low power consumption, and easier operation through smartphone-based analysis systems. Several studies further suggested that hybrid platforms combining both sensing approaches may improve overall sensor performance and usability.

The findings also demonstrated that biomarkers such as glucose, lactate, cortisol, and inflammatory cytokines have strong potential for non-invasive health monitoring. Sweat glucose and lactate showed significant correlations with blood-based measurements, while wearable cortisol sensors demonstrated promising performance for real-time stress monitoring. Inflammatory biomarkers including IL-6, IL-8, TNF- $\alpha$ , and STAMBP were also associated with metabolic and cardiovascular disorders, supporting the potential role of sweat sensing in longitudinal disease surveillance.

In addition, the reviewed studies highlighted the growing integration of wearable sweat sensors within IoMT-based healthcare systems. Bluetooth Low Energy (BLE), cloud computing, machine learning, edge computing, and digital twin technologies enabled continuous real-time

monitoring and improved biomarker analysis. Recent developments also demonstrated the potential of wearable bioelectronics for closed-loop healthcare applications, including automated therapeutic responses based on biomarker detection.

Overall, the findings indicate that wearable sweat sensing technologies provide promising opportunities for continuous, non-invasive, and personalized health monitoring. However, improvements in sensor stability, biomarker validation, and system integration remain necessary for broader clinical implementation.

## Discussion

The reviewed studies demonstrated that electrochemical and colorimetric sensors are the dominant technologies in wearable sweat sensing systems. Electrochemical sensors showed higher sensitivity and analytical accuracy, particularly when integrated with nanomaterials such as MOFs, MXene, and carbon nanotubes<sup>16</sup>. However, challenges including enzyme instability, biofouling, and signal drift remain major limitations for long-term applications. In contrast, colorimetric sensors provided lower production costs, simpler operation, and easier integration with smartphone-based analysis, making them more suitable for large-scale and resource-limited applications<sup>17</sup>. Several studies suggested that hybrid systems combining both approaches may provide improved performance and usability<sup>18,19</sup>.

The superiority of electrochemical sensors is primarily attributed to their high sensitivity, rapid response time, and ability to detect low biomarker concentrations. Nevertheless, their dependence on enzymatic reactions and susceptibility to environmental interference can compromise long-term performance<sup>20,21</sup>. Conversely, colorimetric systems offer greater operational simplicity and affordability but generally exhibit lower analytical sensitivity. Therefore, selecting an appropriate sensing platform should consider the intended clinical application, monitoring frequency, and healthcare setting<sup>22</sup>.

The findings also showed that sweat biomarkers such as glucose, lactate, cortisol, and inflammatory cytokines have significant potential for non-invasive health monitoring<sup>23</sup>. Sweat sensing demonstrated advantages for continuous and real-time monitoring, although plasma-based measurements still provide higher sensitivity for acute clinical diagnosis<sup>5</sup>. Machine learning and artificial intelligence further improved biomarker analysis, signal calibration, and predictive healthcare applications within IoMT systems<sup>24</sup>.

Among these biomarkers, glucose remains the most extensively investigated due to its direct relevance to diabetes management. However, the simultaneous monitoring of multiple biomarkers, including cortisol and inflammatory cytokines, can provide a more comprehensive assessment of metabolic status and disease progression<sup>12,25</sup>. Multiplex sensing platforms could therefore facilitate personalized healthcare by integrating biochemical, physiological, and behavioral information into a single monitoring system.

Despite these advances, several technical challenges remain unresolved. Variability in sweat production, environmental conditions, hydration status, and physical activity can influence biomarker measurements and reduce sensor stability<sup>26</sup>. Biofouling, electrode degradation, and high energy consumption also continue to limit long-term wearable applications<sup>27</sup>. Microfluidic systems and machine learning-based calibration methods were proposed as potential solutions to improve sensor reliability and data accuracy<sup>28</sup>.

In addition, interindividual variations in sweat composition and the absence of universally accepted reference ranges remain major obstacles to clinical translation. Without standardized calibration protocols and validated cutoff values, interpretation of sweat biomarker concentrations can differ substantially among populations, thereby limiting diagnostic reliability. The integration of wearable IoMT devices into healthcare systems also raises concerns regarding data privacy, ethical use of biometric information, and regulatory standardization. Secure data management, transparent artificial intelligence systems, and standardized sweat biomarker reference ranges are necessary before broad clinical implementation can be achieved<sup>17</sup>. In addition, most current validation studies are still concentrated in developed countries, highlighting the need for broader population-based research<sup>29</sup>.

Overall, wearable sweat sensing technologies demonstrate strong potential for future personalized and non-invasive healthcare systems. Future research should focus on improving sensor stability, clinical validation, data security, and the integration of multiplex biosensors with artificial intelligence and IoMT-based healthcare platforms. Large-scale longitudinal studies involving diverse populations are particularly needed to establish standardized sweat biomarker reference values and evaluate the long-term clinical utility of these technologies. The convergence of advanced materials, artificial intelligence, and IoMT infrastructures can ultimately accelerate the development of precision medicine approaches for metabolic disease management.

## Conclusion

IoMT-based wearable sweat sensors have emerged as promising technologies for continuous, non-invasive monitoring of metabolic diseases. This review demonstrates significant advances in electrochemical, colorimetric, and multimodal sensing platforms capable of detecting clinically relevant biomarkers such as glucose, lactate, cortisol, and inflammatory mediators. The integration of wearable sweat sensors with IoMT, artificial intelligence, and cloud-based systems enables real-time monitoring, remote healthcare, and personalized disease management, supporting the transition toward predictive and preventive healthcare. However, challenges related to sensor stability, biomarker standardization, large-scale clinical validation, data security, and regulatory frameworks remain barriers to widespread clinical implementation.

Altogether, wearable sweat sensors should be considered complementary tools within digital healthcare ecosystems rather than replacements for conventional diagnostic methods. Future research

should focus on improving sensor reliability, establishing standardized biomarker references, conducting large-scale clinical studies, and ensuring secure and ethical data management to facilitate the integration of these technologies into routine metabolic disease management.

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