Next-Gen Wearables Unlocking Chemical Secrets

Hossam Haick

In recent years, wearable technology has transcended its initial emphasis on fitness and lifestyle applications, expanding its horizons to encompass a critical role in healthcare and environmental monitoring. This remarkable evolution has been propelled by the advancement of wearable chemical sensors, a burgeoning field that has piqued the interest of both the scientific community and the general public. Wearable chemical sensors are distinct in their unparalleled ability to offer direct and precise insights into our health and surroundings. This trait is crucial in providing real-time insights into various personalised healthcare, environmental safety, and ubiquity of Internet of Things (IoT) that cannot be matched by other sensor types. For instance, these sensors can identify biomarkers in sweat or monitor air quality, yielding critical information that can lead to early disease detection or the identification of environmental risks.

The interdisciplinary nature of the wearable chemical sensors, which integrates materials science, chemistry, electronics, and data analytics, situates them at the vanguard of technological innovation. Unlike other sensors that may have limited scope, wearable chemical sensors can offer comprehensive health monitoring by tracking changes in body chemistry, which may be indicative of various health conditions. This renders them invaluable tools in the quest for personalized medicine. In addition, in the sphere of environmental monitoring, wearable chemical sensors surpass other sensor types in their ability to deliver real-time, localized information about pollutants or harmful substances in the air. This degree of specificity and immediacy in identifying environmental changes is a substantial advantage over other sensor types that may only provide broader, less precise information. Despite the substantial strides made in the field of wearable chemical sensors, the sector faces several challenges. Among these are the miniaturization of sensor components, the enhancement of their sensitivity and selectivity, ensuring durability and reliability in diverse environmental conditions, and addressing data privacy and security concerns. Furthermore, integrating these sensors into wearable devices that are user-friendly and visually appealing remains a critical area of focus.

The latest issue of *Advanced Sensors Research* features a special focus on "Wearable Chemical Sensors," presenting novel studies in this dynamic and rapidly evolving field. An opening article [adsr.202300014] delves into the creation of a Sb-doped SnO_2 nanosphere composite polypyrrole nanohybrid, showcasing its exceptional sensitivity in detecting ammonia. This detailed exploration of nanomaterial properties provides a foundation for understanding the complex interplay between doping ratios and composite structures, which enhances sensor performance in environmental and industrial settings. Expanding on this foundational research, [adsr.202300020] presents a comprehensive analysis of the diverse applications and potential of nanomaterials in gas sensing. This research underscores the pivotal role nanomaterials play in revolutionizing gas sensor technology with enhanced selectivity and sensitivity. These insights are further supported by [adsr.202300021], which examines hydrogel-based flexible chemical sensors. The integration of hydrogel properties with advanced sensing technologies leads to the creation of biocompatible, highly sensitive sensors for wearable devices, medical diagnostics, and environmental monitoring. [adsr.202300035] provides a comprehensive review of room-temperature wearable gas sensors, highlighting their importance in non-invasive health monitoring and environmental detection. These sensors operate at room temperature for enhanced user comfort and wearability, and their integration with emerging technologies such as AI marks a significant stride towards developing smarter, responsive wearable devices. Shifting the focus to additive manufacturing's role in sensor development, [adsr.202300137] presents a review highlighting the transformative potential of 3D printing technology. This technological advancement enables the rapid prototyping of custom, multifunctional wearable devices, democratizing access to advanced diagnostic tools, and addressing healthcare disparities. This narrative of technology as an equalizer in global health weaves a powerful story of innovation and impact.

The intersection of wearable sensor technology and health monitoring is further explored in [adsr.202300036] and [adsr.202300109], which present a complementary story in medical sensor development. These studies shed light on the progression in sensors that continuously monitor essential biomarkers, such as l-lactate and d-glucose, along with vital physiological parameters like heart rate and blood glucose levels. By integrating these sensors into user-friendly devices such as wristbands and smartwatches, they represent a significant shift in patient care, enabling real-time health tracking in everyday life. More than just technological wonders, these sensors signify a move towards personalized healthcare, giving individuals the ability to actively engage in their health management and preventive care. This proactive approach facilitates early detection of health concerns, making healthcare more efficient and tailored to individual needs. In parallel, comprehensive reviews [adsr.202300018] and [adsr.202300009] provide an in-depth analysis of the latest trends in medical sensor technology. [adsr.202300018] explores

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advancements in wound state sensing methods, highlighting the evolution of technologies that improve the monitoring and evaluation of wound healing processes. Complementing this, [adsr.202300009] delves into the emerging field of AI-enabled medical sensors. This review emphasizes the transformative impact of AI integration in sensor technology, enhancing efficiency, accuracy, and personalization in health monitoring. The focus is on AI's ability to process complex health data, paving the way for more tailored and effective health monitoring and interventions. Together, these reviews offer a comprehensive overview of the current landscape and potential future directions in medical sensors, particularly in personalized healthcare driven by technological advancements. An excellent example of the innovative directions discussed is presented in [adsr.202300126], which introduces transcutaneous oxygen tension measurements (TCOM) as a novel, non-invasive method for measuring skin oxygen levels. This technique represents a significant advancement over traditional methods, offering improved patient monitoring and a deeper understanding of oxygenation status. In the field of sports physiology, TCOM holds particular promise as it provides real-time, accurate assessments of oxygenation during physical activity, thereby aiding in optimizing athletic performance.

Environmental monitoring is also at the forefront of this issue, with [adsr.202300061] and [adsr.202300119] focusing on the development of wearable sensors for detecting airborne viruses and volatile organic compounds (VOCs), respectively. Given the COVID-19 pandemic, these innovations are invaluable in providing swift and efficient disease control. The real-time detection of viral exposure is a crucial tool in the ongoing battle against infectious diseases, offering essential data for effective containment strategies. Similarly, the ability to identify VOCs from human breath through non-invasive means offers a pathway for early intervention and more effective treatment strategies in medical diagnostics. Consequently, these sensors are poised to revolutionize the way diseases are detected and diagnosed, ultimately enhancing patient outcomes and public health.

Innovative applications of wearable sensors in agriculture have been thoroughly explored by articles [adsr.202300122] and [adsr.202300107]. These articles examine the development of advanced sensors that can assess vital micro-environmental factors such as soil moisture, nutrient content, and exposure to harmful elements that directly impact crop growth. These state-of-the-art sensors have enabled precision agriculture, allowing real-time data collection and analysis and leading to more informed decision-making in farming practices. This advancement results in enhanced crop yields, waste reduction, and the promotion of more sustainable farming methods. In the rapidly emerging field of wearable sensors for plants, [adsr.202300023] presents a detailed overview of the latest technological advancements. The article showcases innovative sensor designs and their applications in monitoring plant health and interactions with the environment. The sensors play a pivotal role in precision agriculture by enabling real-time data collection on plant physiology and environmental factors, thereby contributing to more sustainable and efficient farming practices.

The articles presented in this special issue showcase impressive strides already taken and outline an exciting trajectory for future advancements. With ingenuity and perseverance, researchers and practitioners are fueling a transformative jour-ney for wearable chemical sensors, poised to redefine healthcare, environmental monitoring, and our interaction with the world. Challenges and opportunities are presented in equal measure throughout the articles. Miniaturization, a significant engineering challenge, presents the opportunity for unobtrusive health monitoring, enabling sensors to be integrated into everyday objects like clothing or personal accessories. This development could lead to a paradigm shift in how health data is utilized, allowing for predictive analytics and personalized medicine on an unprecedented scale.

The management of vast streams of data from wearable sensors is an opportunity to advance the fields of data science and cybersecurity, providing deeper insights into public health trends. This may lead to breakthroughs in understanding and treating diseases. Robust environmental sensors require innovation in materials science and sensor design for sensors that are not only more accurate but also more versatile. Such advancements could allow for real-time monitoring of pollution levels or the detection of hazardous substances, contributing to safer and healthier communities. Scalability offers the opportunity to democratize health monitoring, making advanced wearable chemical sensors accessible to a broader audience. This could reduce the inequities in healthcare access and empower individuals with new tools to manage their health proactively. Navigating regulatory landscapes is an opportunity for standard-setting and assurance of quality and safety in wearable technologies. It can also stimulate international collaboration and harmonization of standards, which is essential for global health initiatives.

The convergence of these challenges and opportunities sets the stage for a future where wearable chemical sensors are an integral part of our daily lives. This special issue serves as both a compendium of the current state-of-the-art and a source of inspiration for the next generation of researchers, entrepreneurs, and policymakers. As guest editor of this special issue, I offer my heartfelt thanks to the authors and reviewers for their pivotal contributions, which shine a light on the path forward, and to our readers, whose engagement is vital in turning these visions into reality. Let us embrace the exciting prospects that wearable chemical sensors hold and forge a better future for ourselves and our world.

Conflict of Interest

The authors declare no conflict of interest.

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Hossam Haick, professor at the Technion, is an expert in the field of nanotechnology and smart sensors. He is the founder and leader of several European consortiums for the development of advanced generations of nanosensors for the fourth industrial revolution and disease diagnosis. His areas of research expertise encompass nanomaterial-based chemical sensors that are flexible, electronic skin, nanoarray devices that can screen, diagnose and monitor diseases, breath analysis, volatile biomarkers, and molecular electronic devices.

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