

Review

Not peer-reviewed version

---

# Wearable Chemical Sensors for Occupational Exposure Monitoring: Technologies, Challenges, and Future Perspectives

---

[Matteo Conti](#)\*, Nini Donatella, [Francesco Saverio Violante](#)

Posted Date: 20 May 2026

doi: 10.20944/preprints202605.1360.v1

Keywords: wearable sensors; chemical sensors; occupational exposure; real-time monitoring; volatile organic compounds; heavy metals; nanotechnology



Preprints.org is a free multidisciplinary platform providing preprint service that is dedicated to making early versions of research outputs permanently available and citable. Preprints posted at Preprints.org appear in Web of Science, Crossref, Google Scholar, Scilit, Europe PMC, OpenAlex.

Copyright: This open access article is published under a [Creative Commons CC BY 4.0 license](#), which permit the free download, distribution, and reuse, provided that the author and preprint are cited in any reuse.

Disclaimer/Publisher's Note: The statements, opinions, and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions, or products referred to in the content.

Review

# Wearable Chemical Sensors for Occupational Exposure Monitoring: Technologies, Challenges, and Future Perspectives

Matteo Conti <sup>1,\*</sup>, Nini Donatella <sup>1</sup> and Francesco Saverio Violante <sup>2</sup>

<sup>1</sup> Industrial Hygiene Laboratory - Occupational Medicine Unit, AUSL Imola, Imola, 40026, Italy

<sup>2</sup> Occupational Medicine Unit - Department of Medical and Surgical Sciences, Alma Mater Studiorum – University of Bologna, Bologna, 40138, Italy

<sup>3</sup> Alma Mater Studiorum – University of Bologna, Bologna, 40138, Italy

\* Correspondence: matteo.conti@ausl.imola.bo.it; Tel.: +39-0542-604913

## Abstract

Occupational exposure to hazardous chemicals remains a major concern across several industrial sectors, including, among others, manufacturing, agriculture, mining, and healthcare. Conventional exposure assessment methods, typically based on stationary environmental monitoring or periodic biological sampling, often fail to capture the dynamic and individualized nature of workplace exposures. In this context, wearable chemical sensors have emerged as promising tools for continuous and real-time exposure monitoring. This exploratory review provides an overview of recent advances in wearable chemical sensing technologies and discusses their potential applications in occupational exposure monitoring. Attention is given to electrochemical, optical, and hybrid sensing systems, as well as to the role of nanomaterials and flexible electronics in improving sensor sensitivity, selectivity, and wearability. Current applications in occupational settings, including monitoring of volatile organic compounds, toxic gases, and heavy metals, are discussed. The review also examines key challenges limiting the practical implementation of wearable sensors in occupational health programs, including long-term stability, environmental interference, power consumption, data integration, regulatory acceptance, and user compliance. Although wearable chemical sensors represent a rapidly evolving field with significant potential for improving occupational risk assessment and preventive strategies, further interdisciplinary research and long-term field validation studies are required before widespread implementation can be achieved.

**Keywords:** wearable sensors; chemical sensors; occupational exposure; real-time monitoring; volatile organic compounds; heavy metals; nanotechnology

---

## 1. Introduction

Occupational exposure to hazardous chemicals remains a major concern in many industrial sectors, in manufacturing, agriculture, mining, and healthcare, among others. Workers in these environments can be subject to a wide range of chemical hazards, such as volatile organic compounds (VOCs), toxic gases, heavy metals, and pesticide residues [1].

Prolonged or repeated exposure to such substances can lead to acute and chronic health effects, including respiratory diseases, neurological disorders, and cancer. According to global occupational health assessments, millions of workers seem exposed to hazardous chemicals each year, highlighting the need for effective monitoring and preventive strategies [2].

Traditional exposure assessment methods typically rely on stationary environmental monitoring systems, periodic air sampling, and/or laboratory-based biomonitoring techniques. While these approaches provide valuable information about environmental contamination levels, they often fail to capture the highly variable and individualized nature of occupational exposure. Chemical

concentrations can vary significantly within a workplace depending on factors such as worker location, activity patterns, ventilation conditions, and process variations. As a result, conventional monitoring methods may not accurately represent the true exposure experienced by individual workers.

Recent advances in wearable sensing technologies offer promising opportunities to address these limitations. Wearable devices capable of continuously monitoring environmental and physiological parameters have gained increasing attention in both healthcare and occupational safety applications [3]. These innovations have established a technological foundation for integrating sensing capabilities into wearable formats such as patches, textiles, wristbands, and badges.

Wearable sensors offer a paradigm shift from reactive to proactive risk management, enabling early intervention and personalized safety measures. Their significance extends beyond individual health, as aggregated data can inform policymaking, exposure limit revisions, and industry-specific safety standards [4].

In parallel with advances in wearable electronics, significant progress has been made in chemical sensing technologies [5]. Wearable chemical sensors are designed to detect specific analytes in the surrounding environment or in biological fluids such as sweat, breath, or interstitial fluid. [4] Notably, in the healthcare sector, pioneering work in epidermal electronics has explored the feasibility of ultra-thin flexible sensor systems capable of conforming to the skin and enabling long-term physiological monitoring [5,6].

Devices typically employ sensing mechanisms based on electrochemical, optical, or conductometric transduction principles. Electrochemical sensors are widely used because of their high sensitivity, relatively low power consumption, and compatibility with miniaturized electronic systems [7]. Optical sensing approaches, including colorimetric and fluorescence-based detection, have also been widely explored due to their high selectivity and potential for simple visual or smartphone-based readout [8].

Over the past decade, advances in nanomaterials and microfabrication techniques have significantly improved the performance of wearable chemical sensors. Nanostructured materials such as MXenes, graphene, carbon nanotubes, metal-organic frameworks, and conductive polymers offer large surface areas and tuneable chemical properties that enhance sensitivity and selectivity [5,9,10]. These materials enable the development of flexible sensing platforms capable of detecting trace levels of hazardous chemicals while maintaining mechanical flexibility suitable for wearable applications.

Several recent studies have demonstrated wearable sensors capable of detecting gases such as ammonia [5,11], hydrogen sulfide [12], and nitrogen dioxide [13], as well as VOCs [14] and heavy metal ions relevant to occupational exposure [15].

Modern wearable systems can transmit data in real time to smartphones or cloud-based monitoring platforms, enabling continuous exposure tracking and advanced data analytics [16,17]. The integration of Internet of Things (IoT) architectures and machine learning algorithms has further enabled automated detection of exposure patterns and predictive risk assessment in occupational environments [3,18,19]. These developments align with broader trends toward digital occupational health monitoring and smart workplace technologies.

Despite these advances, several challenges remain before wearable chemical sensors can be widely adopted in occupational safety programs. Sensor stability and long-term reliability under real-world environmental conditions continue to present significant technical challenges. Industrial environments often involve fluctuating temperatures, humidity variations, and complex mixtures of chemical contaminants that may interfere with sensor performance.

This exploratory review therefore aims to summarize the state of the art in wearable chemical sensors for occupational exposure monitoring, focusing on three critical aspects: sensing technologies and materials used, tested applications in occupational health and safety monitoring, and challenges currently hindering their practical implementation. By providing an integrated overview of current

research, this work aims to highlight emerging opportunities and identify key directions for future development.

## 2. Literature Search Strategy

This study adopts an exploratory review approach to synthesize current research on wearable chemical sensors for occupational exposure monitoring, emphasizing representative and influential studies that illustrate key technological trends and application areas in wearable chemical sensing devices.

The search was conducted in several steps between January 2022 and March 2026, with no language restrictions applied. Literature was identified through searches in several major scientific databases, including PubMed, Scopus, Web of Science, IEEE Xplore, ScienceDirect, and Google Scholar. These databases were selected to capture interdisciplinary research spanning materials science, sensor engineering, occupational health, and biomedical monitoring.

Studies focused exclusively on non-wearable environmental monitoring systems or purely theoretical sensor modelling were excluded. Priority was given to studies published in the last two years (2024–2026) to reflect the most recent technological developments.

Search queries included the following combinations of keywords: “wearable chemical sensors,” “wearable gas sensors,” “occupational exposure monitoring,” “personal exposure sensors,” and “wearable environmental sensors.” Additional terms used to broaden the search and capture technological developments were: “flexible sensors,” “textile sensors,” and “on-body chemical sensing.”

## 3. Results

### 3.1. Recent Trends in Wearable Chemical Sensors Development

Research on wearable chemical sensors has expanded significantly over the past decade, driven by advances in flexible electronics, nanomaterials, and low-power wireless communication technologies. Initial developments in wearable chemical sensing were largely experimental and concentrated on adapting conventional gas sensing technologies into miniaturized and flexible formats. Early prototypes frequently relied on electrochemical, or metal oxide semiconductor sensing mechanisms integrated with portable electronics. These systems demonstrated the feasibility of personal exposure monitoring but were often limited by power consumption, sensor stability, and mechanical rigidity [20].

Recent research has shifted toward the development of flexible and skin-compatible sensing platforms that can be seamlessly integrated into wearable formats such as wristbands, patches, textiles, and badges. Advances in materials science have played a crucial role in enabling these developments. Nanomaterials including graphene, carbon nanotubes, metal–organic frameworks, and conductive polymers have been widely investigated for their high surface area and tuneable chemical sensitivity. These materials enable improved detection limits and faster response times while maintaining mechanical flexibility suitable for wearable applications [21,22].

Another notable trend in the field is the transition from single-analyte sensors to multi-analyte detection systems. Occupational environments often contain complex mixtures of chemical hazards, including volatile organic compounds (VOCs), toxic gases, and particulate-bound contaminants. As a result, recent research has explored sensor arrays and hybrid sensing platforms capable of detecting multiple compounds simultaneously. These systems frequently combine different sensing mechanisms — such as electrochemical, optical, and conductometric detection — to improve selectivity and reduce cross-sensitivity [23].

The integration of wearable sensors with mobile devices and cloud-based data platforms represents another important development. Wireless communication technologies such as Bluetooth Low Energy (BLE), near-field communication (NFC), and Internet of Things (IoT) architectures enable continuous transmission of exposure data to smartphones or centralized monitoring systems.

This connectivity allows real-time analysis of exposure patterns and supports the development of digital occupational health monitoring systems [19].

In parallel with hardware innovation, increasing attention has been directed toward data analytics and intelligent exposure assessment. Machine learning approaches are being explored to improve signal interpretation, compensate for environmental interference, and identify exposure patterns across different occupational settings. These computational techniques can enhance the reliability of wearable sensing systems, particularly when sensors operate in complex and dynamic environments [3].

Environmental robustness represents another key development area. Temperature and humidity compensation algorithms have become standard in modern designs, reducing measurement errors in fluctuating conditions. For instance, Chen et al. incorporated a multi-parameter correction model in their hydrogen sulphide sensor, achieving less than 5% variation across 20–40 °C and 30–90% relative humidity [9,20].

### 3.2. Wearable Chemical Sensor Technologies

Modern sensors primarily employ optical or electrochemical transduction mechanisms, each offering distinct advantages for specific analyte detection. Optical sensors, particularly colorimetric and fluorescence-based systems, dominate gas and VOC monitoring due to their high selectivity and ease of interpretation [24,25]. Colorimetric sensors often utilize indicator dyes embedded in polymer matrices, where analyte-induced colour changes are quantified via smartphone cameras or miniaturized spectrometers [26]. Fluorescence-based sensors provide superior sensitivity for heavy metals such as lead and cadmium. Kidanemariam and Cho reported a textile-integrated sensor based on metal–organic frameworks exhibiting sub-ppb detection limits for these analytes [27].

Electrochemical sensors, including amperometric and potentiometric variants, excel in detecting ionic species and redox-active compounds with high sensitivity. Amperometric gas sensors typically employ enzyme or noble metal catalysts to enhance selectivity. Lehner et al. reported an ultra-sensitive optical oxygen sensor with resolution suitable for monitoring confined or near-anoxic spaces [28]. Potentiometric sensors have been explored for electrolyte monitoring in sweat, particularly for sodium and potassium ions, though their occupational applications remain limited [21]. Graphene and other 2D materials, including MXenes, enable ultra-sensitive detection due to their high surface-to-volume ratios, while conductive polymers provide mechanical flexibility for epidermal applications [9]. Graphene oxide-based sensors have demonstrated approximately 10-fold sensitivity improvements over conventional metal oxide sensors for carbon dioxide monitoring. However, challenges persist in sensor longevity, with many studies reporting performance degradation after 7–14 days of continuous use [29].

Emerging hybrid systems combine multiple transduction principles to overcome individual limitations. Güntner and Schenk integrated optical and electrochemical detection in a single wearable platform, enabling cross-validated measurements of formaldehyde exposure in indoor and occupational settings [30].

### 3.3. Wearable Sensors in Occupational Health and Safety

The application of wearable chemical sensors in occupational settings has demonstrated significant potential for real-time exposure monitoring across diverse industries. These devices address critical gaps in traditional monitoring methods by providing personalized, continuous data that captures temporal and spatial variations in chemical exposure. However, most pilot applications have been addressed to isolated sectors and have not been systematically applied across specific industries [31].

In high-risk environments such as oil refineries, electrochemical sensors dominate due to their robustness and fast response times. Wrist-worn electrochemical systems have achieved high concordance with regulatory-grade monitors for hydrogen sulphide detection, while maintaining operation during physical activities such as climbing and valve operation. However, cross-sensitivity

to other sulphur-containing compounds remains a challenge, requiring algorithmic compensation that can increase power consumption [12].

Agricultural applications present unique requirements for pesticide detection, where colorimetric sensors offer advantages through visual readouts [32]. Patch-based systems incorporating cholinesterase enzymes have been used to detect organophosphate exposure via sweat analysis, demonstrating a clinically significant response within 15 minutes of dermal contact. Field tests showed approximately 78% correlation with blood biomarker levels, though humidity variations above 70% reduced accuracy. This highlights the need for environmental compensation in outdoor settings [33].

The mining sector's focus on heavy metal exposure has driven innovations in fluorescence-based detection. Glove-integrated sensors sampling airborne particulates during routine ore handling have achieved sub-ppb sensitivity for lead through quantum dot-enhanced fluorescence. Microfluidic pre-filters have been employed to overcome dust interference, maintaining high signal stability over 8-hour shifts. Nevertheless, the requirement for periodic reagent replenishment limits practicality for extended underground deployments [34].

Manufacturing environments benefit most from hybrid systems that combine multiple detection principles. Chest-mounted devices simultaneously monitoring formaldehyde via electrochemical detection and toluene via colorimetric sensing have reduced false alarms by approximately 40% compared to single-mode sensors – a critical improvement in paint manufacturing facilities where complex chemical mixtures are prevalent [35].

Healthcare applications present distinct challenges due to the need for sterilization compatibility. Badge-style sensors employing UV-activated optical detection of ethylene oxide have achieved 0.1 ppm sensitivity without interfering with surgical workflows. A six-month hospital trial demonstrated high staff compliance, attributed to lightweight device design and automatic data logging. However, limited battery life necessitated frequent charging, disrupting continuous monitoring during long shifts [36].

**Table 1.** Recent occupational applications of wearable chemical sensors.

Industry Sector	Primary Hazards	Sensor Type	Form Factor	Key Findings	References
Oil & Gas	H <sub>2</sub> S, CO, VOCs	Electrochemical	Wristband	92% accuracy in detecting H <sub>2</sub> S at 10 ppm	[12]
Agriculture	NH <sub>3</sub> , Pesticides	Colorimetric	Patch	15-min response time for organophosphate detection	[33]
Mining	Heavy Metals	Fluorescence	Glove	0.5 ppb Pb <sup>2+</sup> detection in mine dust	[34]
Manufacturing	Formaldehyde, Solvents	Hybrid	Chest-mounted	40% reduction in false alarms vs. stationary sensors	[35]
Healthcare	Disinfectants, Anesthetics	Optical	Badge	Ethylene oxide detection at 0.1 ppm	[36]

Abbreviations: VOCs, volatile organic compounds; H<sub>2</sub>S, hydrogen sulfide.

### 3.4. Wearable Sensors for Healthcare and Biomonitoring Applications

The integration of wearable chemical sensors in healthcare applications represents a critical convergence of occupational exposure monitoring and personalized medicine. These devices bridge the gap between environmental hazard detection and physiological response tracking, enabling comprehensive assessment of chemical exposure impacts on individual health.

Biomarker discovery represents the most prevalent application, where wearable sensors enable non-invasive collection of exposure-related physiological data. Electrochemical platforms capable of simultaneously detecting 8-hydroxy-2'-deoxyguanosine (8-OHdG) and cortisol in sweat have demonstrated strong correlations with oxidative stress levels in pesticide-exposed agricultural workers. This approach overcomes the temporal limitations of traditional biomonitoring by providing continuous data across work shifts, revealing previously undetected circadian patterns in chemical metabolism. However, inter-individual variations in sweat rates can introduce measurement variability, necessitating personalized calibration protocols [21].

Exposure–disease correlation studies leverage wearable sensors to establish quantitative relationships between chemical exposures and subclinical health effects. Optical sensor systems measuring urinary albumin-to-creatinine ratios in industrial workers exposed to cadmium have identified early renal dysfunction at exposure levels below current occupational limits. Longitudinal data collection has demonstrated progressive biomarker elevation in a subset of participants, prompting medical surveillance referrals. This application highlights the potential of wearable sensors to inform revised exposure guidelines based on individual susceptibility rather than population averages [37,38].

Therapeutic monitoring applications remain less explored but show promise for managing acute chemical exposures. Colorimetric wristbands tracking blood acetylcholinesterase activity in organophosphate-exposed individuals can provide real-time feedback on antidote efficacy, potentially reducing clinical decision time compared to laboratory testing. This example underscores the dual-use potential of occupational wearable sensors for both prevention and treatment scenarios [39].

Technical challenges persist in translating laboratory-validated biomarkers to wearable platforms. Protein biomarkers such as cytokines require complex immobilization strategies to maintain stability on flexible substrates, with some studies reporting significant signal loss after hours of continuous wear. Small molecule detection faces interference from endogenous compounds, and urinary metabolite measurements can show cross-reactivity with dietary metabolites — limitations that necessitate rigorous clinical validation before healthcare deployment [40].

The convergence of occupational and healthcare applications introduces unique ethical considerations. Continuous health monitoring blurs traditional boundaries between workplace safety and medical surveillance, raising questions about data ownership and employer liability. Worker concerns about exposure data being used for employment decisions rather than health protection have been reported in the literature, underscoring the need for clear governance frameworks as wearable sensors become more prevalent in occupational medicine [41].

**Table 2.** Recent examples of wearable chemical sensors in occupational biomonitoring.

Applicat ion	Target Biomarkers	Sensor Technolo gy	Biol ogic al Mat rix	Clinical Relevance	References
Biomark er Discover y	8-OHdG, Cortisol	Electroch emical	Swe at	Oxidative stress correlation (r = 0.79)	[21]

Exposure-Disease Linkage	Albumin-Cr ratio	Optical	Urine	Early renal dysfunction detection	[37,38]
Therapeutic Monitoring	Acetylcholinesterase	Colorimetric	Blood	Pesticide poisoning treatment efficacy	[39]

Abbreviations: 8-OHdG, 8-hydroxy-2'-deoxyguanosine.

#### 4. Discussion

The literature reviewed in this study highlights the rapid development of wearable chemical sensors and their growing relevance for occupational exposure monitoring. Advances in materials science, flexible electronics, and wireless communication technologies have enabled the creation of sensing platforms that can be integrated into wearable devices such as wristbands, patches, textiles, and badges. These systems offer the potential to transform traditional exposure monitoring approaches by providing continuous, individualized measurements rather than relying solely on stationary environmental sampling.

A key observation emerging from the literature is the predominance of electrochemical and optical sensing mechanisms in wearable chemical sensor development. Electrochemical sensors are widely used because of their high sensitivity, relatively low power requirements, and compatibility with miniaturized electronics. Optical sensors, including colorimetric and fluorescence-based systems, offer advantages in selectivity and visual interpretation, making them suitable for wearable platforms where simple readout mechanisms are desirable. Recent studies have also explored hybrid sensor architectures that combine multiple sensing principles in order to improve reliability and reduce cross-sensitivity.

Material innovations have played a central role in enabling wearable chemical sensing technologies. Nanostructured materials such as graphene, carbon nanotubes, and conductive polymers provide large surface areas and tunable chemical properties that enhance sensor performance. These materials allow sensors to achieve improved detection limits and faster response times while maintaining the flexibility required for wearable devices. At the same time, challenges remain regarding long-term material stability, environmental durability, and resistance to contamination or fouling during prolonged use in industrial environments.

Another important trend is the increasing integration of wearable sensors with digital monitoring infrastructures. Wireless connectivity and IoT frameworks allow wearable sensors to transmit exposure data in real time to mobile devices or centralized monitoring platforms. Such systems can support advanced exposure analytics, enabling occupational health professionals to identify hazardous conditions more rapidly and implement preventive interventions. The integration of machine learning techniques has been proposed as a means to improve signal interpretation, compensate for environmental interference, and detect complex exposure patterns.

A methodological challenge encountered in this review concerns the classification of studies by target chemical. Unlike physiological wearable sensors, which monitor a limited set of well-defined biomarkers, wearable chemical sensors in occupational settings are designed for highly heterogeneous analyte profiles that vary considerably across industrial sectors. This heterogeneity complicates systematic comparisons and reinforces the value of a narrative approach. Moreover, most pilot applications have been addressed to isolated sectors rather than being systematically applied within a specific industry, limiting the generalizability of findings.

Another methodological challenge was that few studies explicitly reported and evaluated sensor performance against established occupational exposure limits (OELs), such as the Threshold Limit Values (TLVs) defined as time-weighted averages (TWA) over 8-hour work shifts. Future work

should systematically benchmark wearable sensor outputs against these regulatory thresholds to facilitate their integration into compliance monitoring workflows. Closer alignment between sensor development and regulatory frameworks will be essential for these technologies to gain acceptance in formal occupational health programs.

Regulatory considerations emerge as a critical factor in occupational deployment. Only a small number of reviewed studies explicitly addressed compliance with occupational exposure limits (OELs), incorporating real-time alert systems when thresholds were exceeded. The remaining prototypes focused on technical validation without regulatory integration, limiting their immediate practical utility. This gap underscores the need for closer collaboration between sensor developers and occupational health professionals to ensure regulatory relevance.

The integration of sensor data with occupational health management systems remains underdeveloped. While reviewed devices generally provided real-time readouts, automated reporting to institutional safety dashboards was rare. Emerging solutions incorporating blockchain for tamper-proof exposure records and machine learning for exposure pattern recognition show promise in bridging this gap, though their occupational implementation awaits further validation.

Power consumption and device autonomy also represent important design constraints. Although many wearable sensors are designed for low-power operation, continuous monitoring and wireless communication can significantly reduce battery life. Energy-efficient circuit design and alternative power solutions such as energy harvesting technologies may play an important role in extending operational lifetimes.

User acceptance and ergonomic considerations represent another critical aspect of wearable sensor implementation. Devices intended for occupational use must be comfortable, unobtrusive, and compatible with workers' normal activities. Wearable sensors that interfere with mobility or safety equipment are unlikely to achieve high levels of adoption in industrial settings.

Environmental robustness testing by subjecting sensors to full industrial condition simulations including temperature cycles, mechanical vibration, and chemical splashes is a mandatory requirement for real life validation. The lack of standardized testing protocols makes direct performance comparisons challenging and represents an important area for future methodological development. Notably, no reviewed study reported long-term reliability data, reflecting the field's relative immaturity.

The miniaturization of supporting electronics has been equally critical. Low-power application-specific integrated circuits (ASICs) now enable real-time signal processing with minimal energy consumption, extending operational lifetimes to weeks on a single charge. Wireless connectivity options including Bluetooth Low Energy (BLE) and Near-Field Communication (NFC) facilitate seamless data transmission to mobile devices or cloud platforms. Nevertheless, power requirements remain a bottleneck for energy-intensive techniques such as GC-MS, where battery life has been reported at approximately 6 hours despite optimized microfluidic interfaces.

Future research should therefore focus not only on improving sensor performance but also on addressing the broader technological and organizational challenges associated with real-world implementation. Long-term field validation studies are particularly important to evaluate sensor durability, reliability, and user compliance under realistic working conditions. The development of multi-analyte sensing platforms capable of detecting multiple chemical hazards simultaneously could significantly enhance the practical value of wearable monitoring systems in complex industrial environments.

The convergence of wearable sensing technologies with digital health systems also presents promising opportunities. Continuous exposure data collected by wearable sensors could be integrated with physiological monitoring platforms to better understand the relationship between environmental exposures and health outcomes. Such integrated monitoring systems could support more personalized approaches to occupational health management, allowing preventive interventions to be tailored to individual risk profiles.

## 5. Conclusions

This exploratory review has examined the evolving role of wearable chemical sensors in occupational exposure assessment, addressing three key dimensions: technological development, occupational safety applications, and healthcare integration. The findings suggest that these sensors have progressed from laboratory prototypes to field-deployable systems capable of real-time, personalized exposure monitoring. Electrochemical and optical sensing mechanisms dominate current implementations, offering a balance of sensitivity and practicality, though challenges persist in environmental robustness and long-term reliability. The synthesis of evidence confirms their potential to transform occupational health practices by enabling proactive risk management and data-driven safety interventions.

The practical implications are significant. Wearable sensors provide a means to bridge the gap between population-level regulatory exposure limits and individual susceptibility, potentially preventing both acute and chronic health effects. However, widespread adoption requires addressing technical barriers such as power constraints and material stability, alongside organizational challenges including data integration, regulatory alignment, and worker acceptance.

Future research should prioritize longitudinal field studies, standardized performance testing against established occupational exposure limits, and the development of multi-analyte detection platforms. Attention should be given to benchmarking sensor data against regulatory thresholds such as TLVs expressed as 8-hour TWAs, which will be essential for formal acceptance in compliance monitoring. Interdisciplinary collaboration among sensor engineers, occupational health professionals, data scientists, and regulatory bodies will be essential to translate these technological advancements into measurable improvements in occupational health outcomes.

Looking ahead, the convergence of wearable sensors with digital health technologies presents interesting opportunities. Machine learning-enhanced exposure prediction, blockchain-based data integrity, and integration with electronic health records could further enhance the utility of these devices. As the field matures, emphasis must shift from pure technological innovation to holistic solutions that consider ethical, regulatory, and implementation factors. The promise of wearable chemical sensors lies not only in their technical capabilities but in their potential to create safer, healthier workplaces through precision exposure monitoring.

**Author Contributions:** Conceptualization, M.C.; methodology, M.C.; writing—original draft preparation, M.C.; writing—review and editing, N.D. and F.S.V.; supervision, F.S.V. All authors have read and agreed to the published version of the manuscript.

**Funding:** This research received no external funding.

**Institutional Review Board Statement:** Not applicable.

**Informed Consent Statement:** Not applicable.

**Data Availability Statement:** No new data were created or analyzed in this study.

**Conflicts of Interest:** The authors declare no conflict of interest.

**Acknowledgments:** The graphical abstract was created with the assistance of image-generation tools and subsequently reviewed and edited by the authors. Artificial intelligence tools were used to support English language editing and the generation of the graphical abstract. All scientific content, interpretations, and final revisions were critically reviewed and approved by the authors, who take full responsibility for the manuscript content.

## References

1. Badea, D.O.; Darabont, D.C.; Ivan, I.; Ciocîrlea, V.; Stepa, R.A.; Chivu, O.R. Workers' Exposure to Chemical Risk in Small and Medium-Sized Enterprises: Assessment Methodology and Field Study. *Sustainability* **2024**, *16*, 6308, doi:10.3390/su16156308.
2. Shetty, S.S.; D, D.; S, H.; Sonkusare, S.; Naik, P.B.; Kumari N, S.; Madhyastha, H. Environmental Pollutants and Their Effects on Human Health. *Heliyon* **2023**, *9*, e19496, doi:10.1016/j.heliyon.2023.e19496.
3. Mu, G.; Zhang, Y.; Yan, Z.; Yu, Q.; Wang, Q. Recent Advancements in Wearable Sensors: Integration with Machine Learning for Human–Machine Interaction. *RSC Adv.* **2025**, *15*, 7844–7854, doi:10.1039/D5RA00167F.
4. Chen, S.; Fan, S.; Qiao, Z.; Wu, Z.; Lin, B.; Li, Z.; Riegler, M.A.; Wong, M.Y.H.; Oheim, A.; Korostynska, O.; et al. Transforming Healthcare: Intelligent Wearable Sensors Empowered by Smart Materials and Artificial Intelligence. *Adv. Mater.* **2025**, *37*, e2500412, doi:10.1002/adma.202500412.
5. Machín, A.; Márquez, F. Next-Generation Chemical Sensors: The Convergence of Nanomaterials, Advanced Characterization, and Real-World Applications. *Chemosensors* **2025**, *13*, 345, doi:10.3390/chemosensors13090345.
6. Kim, D.-H.; Lu, N.; Ma, R.; Kim, Y.-S.; Kim, R.-H.; Wang, S.; Wu, J.; Won, S.M.; Tao, H.; Islam, A.; et al. Epidermal Electronics. *Science* **2011**, *333*, 838–843, doi:10.1126/science.1206157.
7. Madadelahi, M.; Romero-Soto, F.O.; Kumar, R.; Tlaxcala, U.B.; Madou, M.J. Electrochemical Sensors: Types, Applications, and the Novel Impacts of Vibration and Fluid Flow for Microfluidic Integration. *Biosensors and Bioelectronics* **2025**, *272*, 117099, doi: 10.1016/j.bios.2024.117099.
8. Qian, S.; Cui, Y.; Cai, Z.; Li, L. Applications of Smartphone-Based Colorimetric Biosensors. *Biosensors and Bioelectronics: X* **2022**, *11*, 100173, doi: 10.1016/j.biosx.2022.100173.
9. Chen, R.; Jia, X.; Zhou, H.; Ren, S.; Han, D.; Li, S.; Gao, Z. Applications of MXenes in Wearable Sensing: Advances, Challenges, and Prospects. *Mater. Today* **2024**, *75*, 359–385, doi: 10.1016/j.mattod.2024.04.013.
10. Shao, B.; Chen, X.; Chen, X.; Peng, S.; Song, M. Advancements in MXene Composite Materials for Wearable Sensors: A Review. *Sensors* **2024**, *24*, 4092, doi:10.3390/s24134092.
11. Dong, H.; Li, X.; Liu, Y.; Cheng, W.; Han, C.; Yin, Y.; Li, X.; Shao, C.; Liu, Y. Wearable, Breathable, and Wireless Gas Sensor Enables Highly Selective Exhaled Ammonia Detection and Real-Time Noninvasive Illness Diagnosis. *ACS Sens.* **2025**, *10*, 3964–3975, doi:10.1021/acssensors.4c03468.
12. Shi, N.; Yan, H.; Wang, X.; Liu, G.; Wang, J.; Han, Y.; Duan, Z.; Zhao, G. A Flexible and Wearable PET-Based Chemiresistive H<sub>2</sub>S Gas Sensor Modified with MoS<sub>2</sub>-AgCl@AgNPs Nanocomposite for the Dynamic Monitoring of Egg Spoilage. *Anal. Chim. Acta* **2023**, *1279*, 341836, doi: 10.1016/j.aca.2023.341836.
13. Jiang, X.; Guo, Z.; Zhang, S.; Jia, L.; Wang, Y.; Zeng, X.; Lei, Y.; Liu, H.; Liu, G.; Li, Z.; et al. High-Performance Room-Temperature NO<sub>2</sub> Gas Sensors Enabled by 0D SnO<sub>2</sub> /1D WO<sub>3</sub> Heterostructures for Wearable Applications. *Nanoscale* **2026**, *18*, 4915–4926, doi:10.1039/D5NR03652F.
14. Jamalzadegan, S.; Xu, J.; Shen, Y.; Mativenga, B.; Li, M.; Zare, M.; Penumudy, A.; Hetzler, Z.; Zhu, Y.; Wei, Q. Advancing Wearable VOC Sensors: A Roadmap for Sustainable Agriculture and Real-Time Plant Health Monitoring. *Chem Bio Eng.* **2025**, *2*, 460–474, doi:10.1021/cbe.5c00027.
15. Hu, T.; Lai, Q.; Fan, W.; Zhang, Y.; Liu, Z. Advances in Portable Heavy Metal Ion Sensors. *Sensors* **2023**, *23*, 4125, doi:10.3390/s23084125.
16. Data Analytics and Applications of the Wearable Sensors in Healthcare; MDPI, 2020; ISBN 978-3-03936-351-3.
17. Shahzad, S.; Iftikhar, F.J.; Shah, A.; Rehman, H.A.; Iwuoha, E. Novel Interfaces for Internet of Wearable Electrochemical Sensors. *RSC Adv.* **2024**, *14*, 36713–36732, doi:10.1039/D4RA07165D.
18. Zreikat, A.I.; AlArnaout, Z.; Abadleh, A.; Elbasi, E.; Mostafa, N. The Integration of the Internet of Things (IoT) Applications into 5G Networks: A Review and Analysis. *Computers* **2025**, *14*, 250, doi:10.3390/computers14070250.
19. Guo, H.; Huang, Z.; Zhang, X.; Zhang, H.; Sun, J.; Zeng, Y.; Hu, Y.; Zhou, Y.; Wan, H.; Wang, P. Advancements in Smart Electrochemical Gas Sensors: Bridging IoT, Self-Powering, and Machine Learning for Healthcare. *Sens. Diagn.* **2025**, *4*, 1060–1085, doi:10.1039/D5SD00077G.

20. Jia, Y.; Nithianandam, P.; Liu, T.-L.; Li, J. Development of Wearable Chemical Sensors: An Interdisciplinary Undergraduate Laboratory Experiment Facilitating Knowledge and Expertise Integration. *J. Chem. Educ.* **2023**, *100*, 3595–3603, doi:10.1021/acs.jchemed.3c00379.
21. Akter, A.; Apu, M.M.H.; Veeranki, Y.R.; Baroud, T.N.; Posada-Quintero, H.F. Recent Studies on Smart Textile-Based Wearable Sweat Sensors for Medical Monitoring: A Systematic Review. *J. Sens. Actuator Netw.* **2024**, *13*, 40, doi:10.3390/jsan13040040.
22. Hakeem Anwer, A.; Saadaoui, M.; Mohamed, A.T.; Ahmad, N.; Benamor, A. State-of-the-Art Advances and Challenges in Wearable Gas Sensors for Emerging Applications: Innovations and Future Prospects. *Chem. Eng. J.* **2024**, *502*, 157899, doi:10.1016/j.cej.2024.157899.
23. Peng, M.; Ning, Y.; Zhang, J.; He, Y.; Xu, Z.; Li, D.; Yang, Y.; Ren, T.-L. Wearable Sensing Systems for Multi-Modal Body Fluid Monitoring: Sensing-Combination Strategy, Platform-Integration Mechanism, and Data-Processing Pattern. *Biosensors* **2026**, *16*, 46, doi:10.3390/bios16010046.
24. Duarah, R.; Torné-Morató, H.; Zhang, G.; Amin, Y.; Pabast, M.; Sharma, N.; He, S.; Das, M.R.; Pompa, P.P. Next-Generation Wearable Optical Sensors for Personalized Health and Point-of-Care Diagnostics—A Systematic Review. *Adv. Healthc. Mater.* **2026**, e04419, doi:10.1002/adhm.202504419.
25. Hernik, A.; Smets, J.; Wang, Z.; Semenova, Y.; Tan, J.; Ameloot, R.; Naydenova, I. Optical Detection of Volatile Organic Compounds: A Review of Methods and Functionalized Sensing Materials. *Adv. Opt. Mater.* **2025**, *13*, e00369, doi:10.1002/adom.202500369.
26. Bhakta, S.; Bhattacharya, R. Smartphone-Assisted Colorimetric Sensors: Innovations, Challenges, and Future Directions. *Res.* **2025**, *2*, 100970, doi:10.1016/j.nexres.2025.100970.
27. Kidanemariam, A.; Cho, S. Advanced Metal–Organic Framework-Based Sensor Systems for Gas and Environmental Monitoring: From Material Design to Embedded Applications. *Sensors* **2025**, *25*, 6539, doi:10.3390/s25216539.
28. Lehner, P.; Staudinger, C.; Borisov, S.M.; Klimant, I. Ultra-Sensitive Optical Oxygen Sensors for Characterization of Nearly Anoxic Systems. *Nat. Commun.* **2014**, *5*, 4460, doi:10.1038/ncomms5460.
29. Fernandes, A.C.P.; Vicentini, N.C.; Couto, M.S.; Carvalho, G.R.; Fragneaud, B.; Legnani, C.; Maciel, I.O.; Filho, R.L.F.; Nascimento, J.V.D.C.; Ferreira, J.P.E.; et al. High-Sensitivity CO<sub>2</sub> Sensor Based on a Graphene Oxide Coated Long-Period Fiber Grating. *ACS Omega* **2025**, *10*, 22874–22883, doi:10.1021/acsomega.5c00184.
30. Güntner, A.T.; Schenk, F.M. Environmental Formaldehyde Sensing at Room Temperature by Smartphone-Assisted and Wearable Plasmonic Nanohybrids. *Nanoscale* **2023**, *15*, 3967–3977, doi:10.1039/D2NR06599A.
31. Liu, H.; Wang, Z.; Zhou, G. Wearable Sensors for Monitoring Workplace Chemical Exposures in Occupational Health Management. *Anal. Methods* **2025**, *17*, 7863–7889, doi:10.1039/D5AY00961H.
32. Chu, G.; Yu, S.; Wang, Y.; Zhang, W.; Xue, B.; Huang, J.; Wang, Z.; Luo, J.; Sun, X.; Li, M. A Wearable Electrochemical Sensor for the Monitoring of Neonicotinoid Insecticides, Salicylic Acid and the pH in Plant Guttation. *Chem. Eng. J.* **2024**, *498*, 155340, doi:10.1016/j.cej.2024.155340.
33. Liu, Z.; Zhu, H.; Yang, K.; Liu, Z.; Yang, X.; Ze, Y.; Wang, F.; Zhao, S.; Liu, F.; Chen, B.; et al. A Wearable Electrochemical Sensing Platform for Rapid Detection of Organophosphorus Pesticides: A Flexible Biosensor Based on Screen-Printed Electrodes and Organophosphorus Hydrolase. *Sensors* **2026**, *26*, 2348, doi:10.3390/s26082348.
34. Tsong, J.L.; Robert, R.; Khor, S.M. Emerging Trends in Wearable Glove-Based Sensors: A Review. *Anal. Chim. Acta* **2023**, *1262*, 341277, doi:10.1016/j.aca.2023.341277.
35. Ye, S.; Zhang, Z.; Yang, L.; Li, Z.; Yang, X.; Zhang, J.; Zheng, C. Wearable Formaldehyde Dosimeter for Field-Ready Monitoring of Occupational Exposure and Indoor Air Quality via an Enhanced Hantzsch Reaction. *Anal. Chem.* **2026**, *98*, 6323–6331, doi:10.1021/acs.analchem.5c07756.
36. Chen, X.; Wreyford, R.; Nasiri, N. Recent Advances in Ethylene Gas Detection. *Materials* **2022**, *15*, 5813, doi:10.3390/ma15175813.
37. Thiengsusuk, A.; Youngvises, N.; Pochairach, R.; Taha, R.O.; Sirisabhabhorn, K.; Muhamad, N.; Meesiri, W.; Chaijaroenkul, W.; Na-Bangchang, K. Urinary Albumin-to-Creatinine Ratio (uACR) Point-of-Care (POC) Device with Seamless Data Transmission for Monitoring the Progression of Chronic Kidney Disease. *Biosensors* **2025**, *15*, 145, doi:10.3390/bios15030145.

38. Kalahasthi, R.; Nagaraju, R.; Balachandar, R.; Upadhyay, K.; Bagepally, B.S. Association between Occupational Cadmium Exposure and Markers of Kidney Injury: A Systematic Review and Meta-Analysis. *Chem. Res. Toxicol.* **2025**, *38*, 1638–1651, doi:10.1021/acs.chemrestox.5c00099.
39. Shah, M.M.; Ren, W.; Irudayaraj, J.; Sajini, A.A.; Ali, M.I.; Ahmad, B. Colorimetric Detection of Organophosphate Pesticides Based on Acetylcholinesterase and Cysteamine Capped Gold Nanoparticles as Nanozyme. *Sensors* **2021**, *21*, 8050, doi:10.3390/s21238050.
40. Hsueh, W.-T.; Yu, C.-X.; Cheng, H.-C.; Chen, M.-Y.; Wang, H.-M.; Fu, L.-M. A Comprehensive Review of Wearable Devices for Non-Invasive Biosensing. *TrAC Trends Anal. Chem.* **2025**, *193*, 118425, doi:10.1016/j.trac.2025.118425.
41. Vo, D.-K.; Trinh, K.T.L. Advances in Wearable Biosensors for Healthcare: Current Trends, Applications, and Future Perspectives. *Biosensors* **2024**, *14*, 560, doi:10.3390/bios14110560.

**Disclaimer/Publisher's Note:** The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.