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Wearable sensors for respiratory protection in occupational settings

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A R T I C L E I N F O

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A B S T R A C T

Introduction: Wearable sensors are emerging as potential safety tools for protecting the respiratory health of workers across industries. *Method:* This review summarizes recent research and technological advances in wearable sensors that enable continuous monitoring of respiratory metrics, including personal respiratory health and environmental exposure, across diverse workplaces. The review highlights the integration of these sensors into respirators and face masks for real-time monitoring of respiratory status, exposure, and device integrity. To illustrate the practical implications, the paper discusses representative case studies from high-risk sectors, including mining, firefighting, healthcare, construction, and oil and gas. *Results:* This review reveals that, although several types of wearable respiratory sensors are available for public use, only a few are specifically tailored for occupational respiratory protection. Efforts toward field validation, standards development, user acceptance, and regulatory compliance are needed to translate prototypes into practical tools for occupational risk mitigation. *Conclusions:* The future of workplace respiratory safety will also benefit from the integration of these sensors with emerging technologies such as artificial intelligence, machine learning, the Internet of Things, and computer vision. *Practical Applications:* This study provides an overview of the current state of wearable respiratory sensors, identifies outstanding challenges that hinder their widespread adoption in occupational settings, and outlines potential avenues for future research to translate them into validated occupational safety tools.

1. Introduction

Respiratory hazards pose significant risks to workers' health and safety across industries, making them a major concern in the workplace. These hazards primarily include: insufficient oxygen; airborne substances such as toxic gases, smoke, and dust particles; airborne pathogens; and radioactive aerosols (Occupational Safety and Health Administration (OSHA), 2025; Szalajda et al., 2025). To protect workers from these hazards, a hierarchy of control consisting of elimination, substitution, engineering controls, administrative controls, and personal protective equipment (PPE) has been implemented for decades (National Institute for Occupational Safety and Health (NIOSH), 2024). In this framework, PPE is used as the last line of defense when other measures are not feasible or sufficient (NIOSH, 2024). While PPE remains crucial, advancements in technologies such as advanced sensors, the internet of things (IoT), artificial intelligence (AI), and computer vision have created opportunities to improve risk assessment and enhance workplace safety (Asadzadeh et al., 2020; El-Helaly, 2024; England et al., 2023a, 2023b).

Wearable sensing technologies are of particular interest for their ability to provide users and controllers with real-time information about potential risks and hazards without disrupting work processes (Howard et al., 2022). These sensors can be tailored to continuously monitor personal conditions (e.g., health, physiological state, physical activities), location, and environmental factors (e.g., temperature, humidity, pressure, chemical hazards, physical agents, and biological contaminants) and provide feedback in real time (Awolusi et al., 2018; Decaens & Vermeersch, 2016; Howard et al., 2022; Patel et al., 2022; Svertoka et al., 2021). Many of these sensors have become increasingly popular among the public for purposes such as fitness tracking, rehabilitation, personal health monitoring, clinical assessments, and even learning enhancement (Andrea, 2017; Dias & Paulo Silva Cunha, 2018; Khosravi et al., 2022; Patel et al., 2012; Smith et al., 2023). In occupational settings, these devices hold great potential to mitigate injuries, illnesses, and fatalities (Awolusi et al., 2018; Moon & Ju, 2024; Svertoka et al., 2021). For example, PPE equipped with moisture sensors has been proposed to help firefighters combat heat stress (Bernhart et al., 2024). Similarly, wearable kinematic and physiological sensors have been

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proposed to assist miners with monitoring dynamic motion, stress, and fatigue in confined spaces (Sadeghi et al., 2022). Wearable sensors for gases, volatile organic compounds (VOCs), chemical vapors, particulate matter (PM), dust, and physiological parameters (respiratory rate, heart rate, tidal volume, etc.) have direct relevance to enhancing respiratory safety across industry sectors (Asadzadeh et al., 2020; Coleman, 2021; Dias & Paulo Silva Cunha, 2018; Fanti et al., 2022; Howard et al., 2022; Hussain et al., 2023; Hyysalo et al., 2022; Schmitt, 2022; Vanegas et al., 2020). These sensors can trigger actionable alerts to workers and controllers based on the severity of these respiratory hazards. In recent years, capabilities and application areas of wearable sensors have increased significantly due to the advancements in enabling technologies such as materials science, fabrication technologies, electronics, IoT, and machine learning (ML) (Hadi et al., 2025; Mu et al., 2025; Vaghasiya et al., 2023).

Research and technological advances in wearable sensor technologies for various applications have been covered in several review papers (Aroganam et al., 2019; Patel et al., 2012; Svertoka et al., 2021). Although there exist excellent reviews on the wearable sensors for monitoring physiological parameters and environmental variables that hold potential for protecting workers (Awolusi et al., 2018; Svertoka et al., 2021), there is a relatively small volume of literature dedicated to workplace safety and health (Mihailescu, 2023; Moon & Ju, 2024; Suryawanshia et al., 2024). Specifically, reviews focused on the applications for occupational respiratory safety are lacking, partially because this application is relatively new and gained increasing attention during the past few years (Hussain et al., 2023; Moon & Lee, 2023; Nicolò et al., 2020; Vitazkova et al., 2024). This review aims to fill that gap by concentrating on these sensors that are currently applied or have potential in monitoring respiratory metrics within various work environments.

The next section outlines the approaches used to search and select literature and describes the limitations of the review. Then, we discuss the types of respiratory hazards commonly encountered in various workplaces and their associated health effects, followed by an overview of the system architecture and key enabling technologies behind wearable sensors. Next, we review the applications of these sensors for monitoring human-centric and environmental factors relevant to respiratory health in different work environments. We then discuss sensors integrated into face masks and respirators for monitoring a range of parameters followed by representative case studies from high-risk industry sectors. Finally, we discuss outstanding challenges to widespread adoption, highlight potential research directions to overcome these barriers, and conclude with a summary of our findings.

2. Methods and limitations

Relevant scholarly literature, including journal articles, technical reports, and online blogs, was accessed using various search engines such as Google Scholar, Scopus, PubMed, IEEE Xplore, and Web of Science. The Centers for Disease Control and Prevention (CDC) library and AI-assisted tools (e.g., CDC Chatbot, Liner Basic, ChatGPT, and Google Gemini) were used for refining search strategies. Major keywords included "wearable respiratory sensors," "wearable sensors for respiratory hazards," "wearables for respiratory physiological parameters or vital signs," "respiratory health monitoring in workplaces," "respiratory health monitoring in high-risk industries (i.e., mining, construction, healthcare, firefighting, oil and gas)," "real-time monitoring of occupational exposure," "wearable respiratory sensor systems," "sensor-integrated respirators and face masks", and "applications of wearable respiratory sensors in occupational settings." The suitability of each publication was evaluated based on its title and abstract and it was included only if it addressed wearable sensors or real-time monitoring of physiological parameters or exposure. Selected review articles on wearable sensors were examined to identify the general architecture and key components. Original studies focused on monitoring at least one respiratory parameter in occupational settings were reviewed in detail to synthesize relevant findings.

It is important to note that there are several limitations to this study. First, the review was conducted to provide an overview of wearable sensors and systems for physiological parameters and exposure monitoring, and their major advancements in monitoring respiratory health-related parameters in occupational settings, rather than to perform a deep analysis. Second, priority was given to the research publications and technical reports that were either available in recent peer-reviewed publications, on well-known sites such as NIOSH blogs, or as well-documented commercial systems. Emphasis was given to more recent (2020–2025) technical publications, although some earlier publications were included to review general concepts about wearable sensors and occupational respiratory risks. Reviews focused on selected publications that provided diversity in development and applications, rather than all available works. Publication sources, trends, and counts were not analyzed. Only publications in English were considered.

3. Respiratory hazards in occupational settings

Respiratory hazards are substances, physical factors, or conditions that can pose a risk to the respiratory system. These include toxic gases (e.g., carbon monoxide (CO), hydrogen sulfide (H_2S), ammonia (NH_3), nitrogen dioxide (NO_2), methane (CH_4) and sulfur dioxide (SO_2)), chemical vapors, fumes, smoke, dust, allergens, bacteria, fungi, and viruses, and PM. Similarly, insufficient oxygen (O_2), high carbon dioxide (CO_2), and radiological exposure can also pose challenges in respiratory health. In addition, environmental conditions such as temperature, pressure, and humidity levels may exacerbate airborne contaminants in a workplace (Qiu et al., 2022). These respiratory hazards have long been recognized in various workplaces (NIOSH, 2019), but their types and concentrations are unique to occupational settings (OSHA, 2012; National Research Council and Institute of Medicine, 2008; Kasangaki, 2025; Linaker & Smedley, 2002; Lynch, 2024). Table 1 gives an overview of common respiratory hazards in various industry sectors, including high-risk industries like mining, firefighting, healthcare, construction, manufacturing, and oil and gas (Kasangaki, 2025; Linaker & Smedley, 2002).

Exposure to respiratory hazards can cause numerous respiratory diseases, including lower and upper airway diseases, interstitial lung diseases (e.g., black lung disease, asbestosis, silicosis), respiratory tract and pleural malignancies (e.g., lung cancer, mesothelioma), asthma, and lung fibrosis (Kasangaki, 2025; Linaker & Smedley, 2002; Murgia et al., 2024). Based on the 2019 Global Burden of Disease Study, chronic respiratory diseases were responsible for 4 million fatalities, making them the third leading cause of death globally (Momtazmanesh et al., 2023). Other studies have also discovered that occupational exposures significantly contribute to many respiratory diseases (Cullinan et al., 2017; de Perio et al., 2020), including infections and up to 10% of community-acquired pneumonia cases. According to a joint study by the American Thoracic Society and the European Respiratory Society in 2019,

Table 1
Common respiratory hazards in various industry sectors.

Industry sector	Common respiratory hazards
Healthcare	Infectious aerosols, pathogens (including viruses and bacteria), chemical disinfectants, anesthetic gases
Mining	Coal dust, silica dust, PM, toxic gases
Construction	Dust, vapors, aerosols, asbestos, fumes
Manufacturing	Dust, chemical vapors, gases, fumes, mists
Firefighting	Smoke, PM, dust
Agriculture, Forestry, & Fishing	Pesticides, chemical vapors, toxic gases, slurry, fertilizers, mold spores, organic dust with allergens, bacteria, fungi
Oil and Gas	PM, hydrocarbon gases, H_2S
Transportation	Vehicle emissions, dust, chemical fumes
Textile	Organic cotton dust, endotoxins

workplace exposure may be responsible for a range of nonmalignant lung diseases in more than 1 in 10 people worldwide (Blanc et al., 2019). The study also showed that the occupational burden of tuberculosis may be 2.3% in silica-exposed workers and 1% in healthcare personnel (Blanc et al., 2019). Upper respiratory infections and lower respiratory infections had estimated incidences of 17.2 billion and 488.9 million cases, respectively (Jin et al., 2021; Safiri et al., 2022). In 2016, the United States spent $170.8 billion on respiratory conditions, which was a significant portion of healthcare spending (Duan et al., 2023).

Respirators and face masks are the most common types of face-covering devices, with respirators providing respiratory protection and face masks serving primarily as source-control barriers in both community and occupational settings (Bhattacharjee et al., 2022; MacIntyre & Chughtai, 2015). Their effectiveness can be compromised by failure, improper use, or misuse (Aqueveque et al., 2022), and there are concerns about adverse physiological and psychophysiological effects due to their prolonged or improper use (Buzzin et al., 2022; Szeinuk et al., 2000). In addition, failure to comply with safety regulations remains a concern in various occupational environments. According to the Occupational Safety and Health Administration (OSHA), respiratory protection was among the 10 most frequently cited safety standards in 2023 (OSHA, 2023). OSHA stated that, "Compliance with the OSHA Respiratory Protection Standard could avert hundreds of deaths and thousands of illnesses annually" (OSHA, 2025).

4. Wearable sensing systems and key components

A functional wearable sensing system comprises several enabling technologies, including sensor devices, power sources, processing and control electronics, material technologies, wireless communications, data processing and analytics, and user interfaces (Bonato, 2010; Patel et al., 2012). There are significant variations in system architecture, technologies, and components, depending on application requirements, technology types, and placement locations amongst others. Fig. 1 shows a typical wearable sensing system and its enabling technologies. These enabling technologies are either hardware- or software-based and can generally be grouped into three key categories: sensor nodes for sensing and data collection, communication channels for data transmission and communication, and data analytics units for signal processing, analysis, and user feedback (Mamun & Yuce, 2019).

The sensing and data collection unit (i.e., sensor node), interacts with the analytes and/or the monitored environment and converts the interaction into a processable signal. The collected data are transmitted to a processor, interrogator or gateway, where it undergoes initial storage, basic analysis, and is converted into digital signals. Subsequently, the data are forwarded to a computer, a centralized computing server, or a cloud/web server for advanced analysis, which ultimately generates actionable information. User feedback is generated based on this information. In most wearable sensing systems, the data collection unit is worn by the user, while the remaining units may be located remotely, such as at the user's or controller's location, or may be integrated with the wearable sensor node. Wearable health monitoring systems used in telemedicine can be considered examples of such remotely controlled systems. Some systems, such as smartwatches, have all the units integrated into a wearable package in which the user has immediate access to the information. It is important to note that wearable packages may also send the final data to remote controllers or users. Readers who are interested in detailed information about the enablers and components of various wearable sensing systems are referred to available references (Mamun & Yuce, 2019; Patel et al., 2012; Perez & Zeadally, 2021; Smith et al., 2023). Here, we briefly review and discuss some of these technologies that enable wearable systems for monitoring various parameters, especially in occupational settings.

4.1. Sensor node

A sensor node in a wearable sensing system is a wearable unit that consists of at least one sensor device to interact with its environment and collect data about the user's physiological status, physical activities, or other variables in the immediate surroundings (Antolín et al., 2017; Ates et al., 2022; Khan et al., 2019). In terms of functionalities, these sensor devices can be categorized as physical or chemical (and bio) sensors (Antolín et al., 2017; Hulanicki et al., 1991; Khan et al., 2019). A physical sensor is a transducer used to measure one or more physical parameters such as temperature, pressure, motion, position, and others. The information contained by these parameters can be processed to monitor various physiological signals, including body temperature, heart rate, blood O_2/CO_2 level, and breathing rate (Dias & Paulo Silva Cunha, 2018; McGrath & Scanaill, 2013; Svertoka et al., 2021). Chemical and bio sensors are the detectors for a range of analytes in gaseous and liquid-phases, such as humidity, chemical vapors, gases, PM, pH, electrolyte solutions, biomolecules, and pathogens (e.g., bacteria, viruses) (Hulanicki et al., 1991; Khan et al., 2019). Common sensing principles used in wearable sensors include electrochemical, optical,

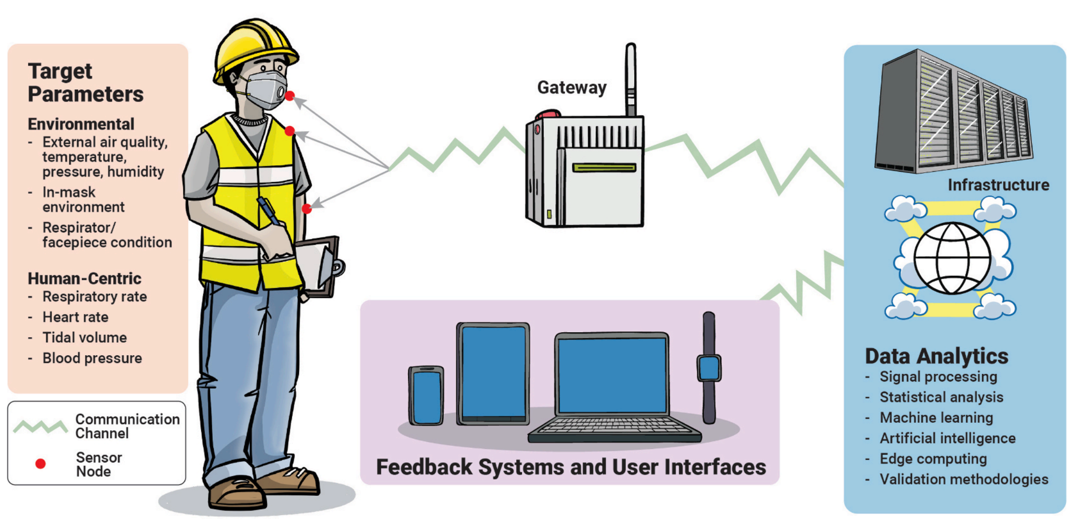

Fig. 1. Conceptual architecture of a wearable sensing system for occupational respiratory protection. Sensor nodes measure environmental conditions (air quality, temperature, pressure, humidity, in-mask conditions, facepiece status, etc.) and human-centric parameters (respiratory rate, heart rate, tidal volume, blood pressure, etc.). Data are transmitted to an analytics module that generates real-time information for hazard detection, breathing assessment, and respirator performance monitoring and enables timely user alerts or control actions through a feedback system.

mechanical, electrical, and acoustic methods (Fig. 2(a-g)), each of which has trade-offs in sensitivity, selectivity, and durability (Hussain et al., 2023; Li et al., 2023; Mihailescu, 2023; Vanegas et al., 2020).

In addition to these front-end sensor devices, a sensing unit may also contain additional hardware such as power source, microcontroller, communication hardware, reader, and accessory microelectronics circuitry. These components may be embedded or integrated along with the sensor device or placed nearby. The specific components of such an integrated unit depend on the sensing technology type and targeted application (Bonato, 2010; Mamun & Yuce, 2019; Patel et al., 2012). Fig. 2(h) shows an integrated sensing unit on a flexible, printable circuit board (PCB) (Gao et al., 2016), which consists of wearable sensor arrays for data collection, as well as a microcontroller, a Bluetooth antenna, and microelectronics circuitry for data processing and wireless transmission. A network of these sensor devices can be formed to monitor multiple parameters simultaneously at multiple points and provide comprehensive information. These networks are commonly referred to as body area networks (BAN), body sensor networks (BSN), or wireless sensor networks (WSN) depending on the variations in their placement and architecture (Dias & Paulo Silva Cunha, 2018).

A wearable sensor must be sensitive, selective, accurate, reproducible, reliable, and low-cost, similar to fixed-area sensors for work environments. In addition, comfort, compatibility, ease of use, and user acceptability play critical roles in adoption and use of wearable technology. Therefore, wearable sensors are expected to be smaller, lighter, unobtrusive, flexible, power efficient, and wireless while maintaining accuracy and reliability in their performance (Xue et al., 2024). Accordingly, recent research has focused on improving the performance, miniaturizing the components of the sensing unit including sensor devices, microcontrollers, and electronic circuits as well as reducing power requirement amongst others (Patel et al., 2012). Radio frequency (RF) and microwave-based sensor devices have recently attracted attention for their inherent wireless capacity to simultaneously power the sensors and transmit data (Costanzo et al., 2023; Devkota et al., 2020; Devkota et al., 2017). Magnetic sensors based on RF impedance or magneto-impedance effect are also emerging as wearable devices for real-time health monitoring (Jimenez et al., 2022). These RF-based passive devices could significantly reduce the circuit complexity, device size, and weight while enhancing user safety by eliminating battery-related hazards. Recent progress on advanced materials (including nanomaterials, nanoporous materials, 2D materials, and flexible materials) and fabrication technologies (including 3D printing and microelectromechanical system (MEMS) techniques) has helped improve the performance and reduce the form factor and weight of these sensors, enabling them for a wide range of applications (Fahimi et al., 2019). Readers interested in learning more about advanced materials and fabrication techniques of wearable sensors are referred to available literature (Ates et al., 2022; Ellis et al., 2021; Fazio et al., 2021; Isaac et al., 2022; Nguyen et al., 2021; Suo et al., 2022; Vaghasiya et al., 2023; Yang et al., 2017; Yin et al., 2024).

Wearable sensor nodes can be placed on the body in several ways: (i) by implanting into the body; (ii) by touching the body surface or skin (e.

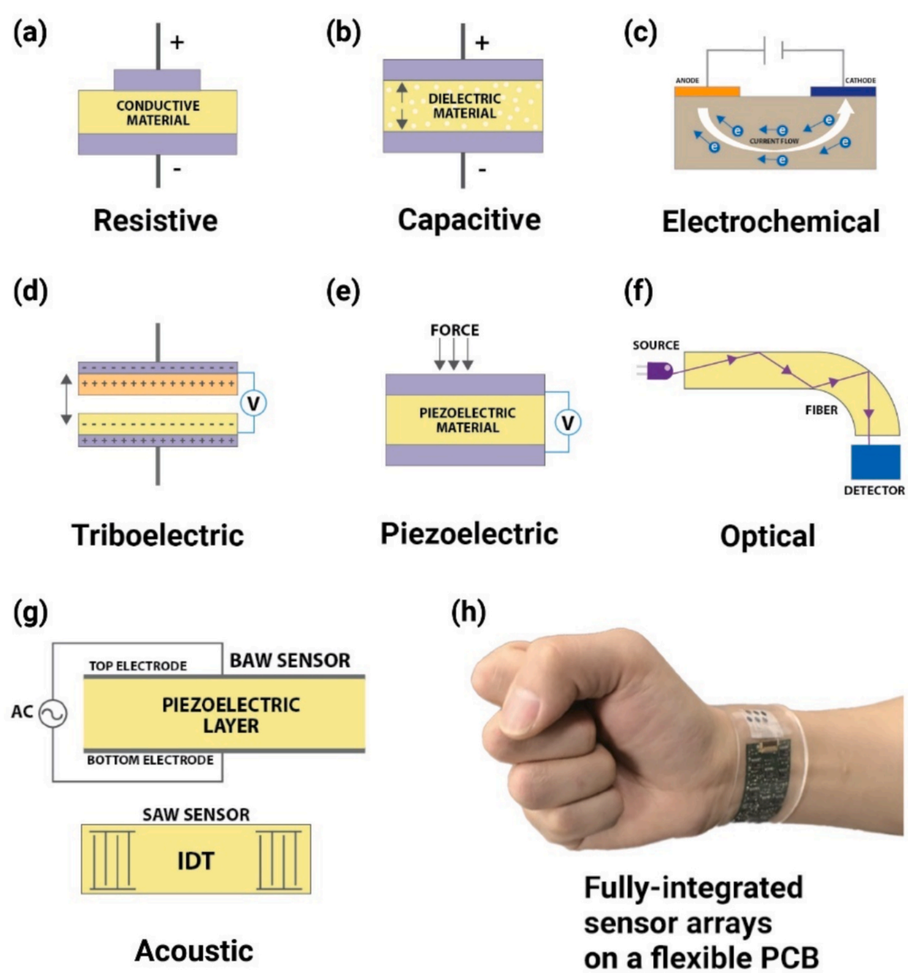

Fig. 2. Examples of sensing technologies and an integrated wearable sensing unit. Panels (a–g) illustrate common sensing technologies for wearable sensors and panel (h) shows a fully integrated sensor node (i.e., sensing unit) as a smart wristband that comprises flexible sensor array devices and accessory electronics on a wireless flexible printed circuit board (PCB). Panel (h) was reprinted from reference (Gao et al., 2016), with permission from Springer Nature.

g. worn as wristband, as shown in Fig. 2(h)); or (iii) by integrating or attaching them to clothing, PPE, other wearable devices, or personal belongings (Bonato, 2010; Mardonova & Choi, 2018; Perez & Zeadally, 2021). The optimal placement depends on various factors, including application requirements, sensor type, user comfort, and reachability. Feasible options for respiratory protection in occupational settings include integrating or attaching sensors to safety gear, PPE, or other wearables as well as placing them on the skin. Most commercial wearable sensors available today are integrated with other wearable devices such as smartwatches, smartphones, and smart glasses (Escobar-Linero et al., 2023).

4.2. Communication and data analytics units

The communication unit is a pivotal component within wearable sensing systems that facilitates the transfer of collected data from sensor devices to a control unit or gateway for subsequent analysis and all other communications among various components or units of a sensing system (Fig. 1). This block typically comprises data transmission hardware and circuitry that establish communication among sensor devices or between sensor devices and interrogation or user interface through various means, including cables, fiber optics, or wireless links using established protocols or custom antennas (Tocco et al., 2021; Usman et al., 2018). While communications through wires or optical fibers are relatively secure, they are not practical for wearable devices. Tocco et al. developed a wearable system based on optical fiber Bragg grating (FBG) sensors for unobtrusive respiratory monitoring in occupational settings (Tocco et al., 2021). Although sensor performance was promising, mobility was a major limiting factor for practical use of such systems. To overcome this limitation, wireless technologies have emerged as the preferred option for data transmission and communication.

There are several wireless protocols that facilitate communication between sensor devices and interrogators, allowing the seamless transmission of collected data to a receiver embedded within the interrogator and enabling power transfer to the sensors in certain cases. For workplace wearable sensors, short-range (<100 m) wireless protocols such as Zigbee, Bluetooth, radio-frequency identification (RFID), near-field communication (NFC), and custom short-range antennas are commonly used for communication between sensor devices and interrogators (Coskun et al., 2013; Custodio et al., 2012; Svertoka et al., 2021). However, in some cases, mid-range (100 m–5 km) protocols such as Wi-Fi (IEEE 802.11x, x = b, g, n, ac) and long-range (>5 km) protocols such as LoRa and LTE are more appropriate (Svertoka et al., 2021). A comprehensive discussion of wireless in-body or off-body communications, along with their associated security challenges was given by Usman et al. (Usman et al., 2018). Table 2 summarizes commonly used short-range wireless communication technologies utilized for transmitting data from sensing units to control units, gateways, or interrogators.

At the interrogator level, basic signal processing techniques such as averaging and noise filtering are often employed to enhance the quality of the transmitted data. Following these preliminary processing steps, the refined information is transmitted to a computer or web server for comprehensive analysis (see the 'Data Analytics' section in Fig. 1). At this stage, advanced analytics techniques, including ML, deep learning, and AI can be employed for automation, pattern recognition, and extraction of other useful information, such as suitable data for feedback generation (Mu et al., 2025). The analyzed data can also be integrated with IoT technologies for purposes such as tracking trends, predicting potential health risks, and ensuring compliance with safety regulations (Hyysalo et al., 2022). The analyzed data can be made accessible to users and controllers through various feedback systems and interfaces including visualizations, auditory alerts, and haptic feedback (Fig. 1) (Shin et al., 2024). In recent years, cloud-based communication, data storage, and computing have been another emerging technology to help advance the functionality of wearable sensors (Sinnapolu & Alawneh, 2018).

Table 2
Common short-range wireless communication technologies for wearable sensors (Mamun & Yuce, 2019; Ometov et al., 2021; Park et al., 2019; Svertoka et al., 2021).

Wireless technology	Frequency band (MHz)	Power requirement	Approximate range (typical)	Maximum data rate
NFC (Ometov et al., 2021; Park et al., 2019)	13.56	Very Low	≤20 cm	424 kbps
Bluetooth (Park et al., 2019)	2400	Medium	≤100 m	24 Mbps
Bluetooth Low Energy (BLE) (Ometov et al., 2021)	2400	Low	≤100 m	24 Mbps
Zigbee (Ometov et al., 2021; Park et al., 2019)	868, 915, 2400	Low	10–100 m	20 kbps, 40 kbps, 250 kbps
RFID (Ometov et al., 2021)	0.125 – 0.134, 13.56, 860 – 960	Very Low, Passive	≤100 m (frequency dependent)	100kbps (frequency dependent)
Custom Resonant Antenna (Park et al., 2019)	Design/Type dependent	Very Low, Passive	~1 m (frequency dependent)	~100 kbps (frequency dependent)

5. Applications for occupational respiratory protection

The parameters relevant to respiratory health that can be monitored by wearable sensors include several human-centric (i.e., physiological) and environmental parameters. Environmental parameters encompass both the external breathing environment and the in-mask micro-environment, as well as respirator or face mask conditions. Continuous measurement of physiological parameters such as respiration rate, oxygen saturation (SpO_2), breathing patterns, and pulmonary ventilation enable detection of respiratory distress in real time (Andrea, 2017; Tocco et al., 2021). Additionally, CO_2 buildup inside respirators and face masks is directly related to breathing comfort and perceived exertion (Akhondi et al., 2022; Johnson, 2016). Key external environmental factors include air quality (e.g., toxic gases, PM, dust, VOCs), ambient conditions (e.g., O_2 and CO_2 levels, temperature, pressure, humidity), and airborne biohazards (e.g., viruses and bacteria) (Kuglics et al., 2024; Li et al., 2023; Li et al., 2023; Svertoka et al., 2021; Tian et al., 2016). Early research on wearable sensors for respiratory monitoring applications focused on assessing the physiological parameters of patients within healthcare systems (Bonato, 2010; Yilmaz et al., 2010). Their application in workplace settings has gained significant attention in recent years (Patel et al., 2022). For successful implementation in occupational settings, these sensors must possess specific features such as a small form factor, lightweight design, wireless communication capability, and user acceptability, in addition to typical sensor characteristics. Additional features, including the capability to monitor multiple physiological and environmental parameters, battery-free operation, and the integration of advanced data analytics, further increase the usability of these sensors. Appropriate placement, integration into appropriate PPE and gear, and optimized feedback system are crucial for reliability, effectiveness, and generating actionable alerts. There are multifaceted efforts to tailor sensor devices with optimized features for use in diverse workplaces to enhance safety and user comfort (Algamili et al., 2021; Antolín et al., 2017; Campero-Jurado et al., 2020; Khan et al., 2019; Li et al., 2023).

5.1. Monitoring human-centric parameters

Real-time monitoring of respiratory physiological parameters in workplaces can provide timely information about workers' respiratory health status and potential risks, reducing or even eliminating the need for periodic medical visits (Jia et al., 2025). For instance, onsite measurement of respiration rate can indicate respiratory distress or abnormal breathing patterns (e.g., irregularities, shallow breathing), which in turn can provide insights into wearer's current respiratory health status. Additionally, measurements of oxygen saturation levels can reveal compromised oxygen availability in workplaces, alerting workers to precautionary actions. Online measurements of other parameters, such as pulmonary ventilation, can provide information about airflow inside and outside the lungs and potential systemic issues, respectively, while a worker is in the workplace.

There are several commercially available and prototype stage wearable sensors focused on monitoring respiratory physiological parameters (Andrea, 2017; Jia et al., 2025; Konno & Mead, 1967; Mirjalali et al., 2022; Patel et al., 2012; Patel et al., 2022; Smith et al., 2023). Pulse oximeters, for example, are commercially available wearable sensors used to measure oxygen saturation levels in the blood (Andrea, 2017). These devices are available as stand-alone units or embedded in other wearables, such as smartwatches and ear amplifiers (Andrea, 2017). Examples of devices that are at the developmental stage include a smart belt designed by Lukocius et al. (2014), which integrate electrocardiography and inductive plethysmography sensors to monitor workers' respiratory and the cardiovascular functions. The proposed system could transfer data wirelessly and included an algorithm to calculate respiratory rate from the sensor data collected during rest or motion. The authors suggested that the system could be utilized for monitoring workers' physiologic responses to work in occupations that demand intensive physical activity. Similarly, optical fiber-based wearable sensor systems are being developed to monitor the respiratory rate in occupational settings (Krehel et al., 2014; Tocco et al., 2021). These devices do not need battery at the sensing location, can monitor multiple parameters, and are compatible with advanced data analytics methodologies. As a result, they are attractive for monitoring respiratory parameters in the workplace, despite limitations such as the need for an external interrogator connected to the sensing unit. With increased interest in comprehensive health monitoring in workplaces, efforts have been made to develop sensors for multiple physiological parameters, including respiratory vital signs (Bustos et al., 2021; Li et al., 2023). For example, Li et al. developed an AI-assisted, low-cost, and self-powered wearable sensor system for multiple physiological parameters based on a triboelectric nanogenerator (TENG). The sensor system was able to detect signals under various breathing states and environmental conditions as well as transfer the data wirelessly. While their sensor system was a lab-based demonstration and focused on portable healthcare applications, the product could potentially be utilized in an occupational setting as well. Similarly, there have been several efforts toward developing multi-parameter sensors integrated into respirators and face masks to evaluate the performance and integrity of these face-covering devices, monitor the breathing pattern and in-mask environment, and detect pathogens in the surrounding environment (Grinshpun et al., 2020; Zhong et al., 2022). These measurements can provide insights into breathing conditions, perceived exertion, fatigue, potential leaks, and exposure in real time, thereby allowing users to take precautionary actions (Pinnelli et al., 2024; Suo et al., 2022; Wu et al., 2018). There are concerns regarding motion artefacts and low perfusion in these devices. However, recent advancements in data analytics have made it possible to minimize these effects (Andrea, 2017; Mu et al., 2025).

5.2. Monitoring environmental parameters

Environmental parameters relevant to respiratory protection include the external breathing environment, the in-mask micro-environment, and the condition of respirators and face masks. Portable sensor systems for air contaminants, including gases, particulates, and pathogens, can provide early warnings about exposure, thereby helping to protect workers from respiratory hazards. Unlike fixed-area monitors, these sensors can be easily deployed in confined areas and integrated with physiological sensors and location tracking, which is not feasible with fixed-area monitors.

There are a few commercial wearable sensors available for the detection and monitoring of harmful gases, dust, and other environmental variables (Patel et al., 2022). Examples include photoionization-based detectors from Ion Science, Inc. (Ion Science, Inc., 2025) and light-scattering-based detectors from Reactec Ltd. (Reactec Ltd., 2023), which can provide real-time feedback about exposure in workplaces. Additionally, there are several research efforts to develop low-cost, miniaturized sensor systems with capabilities for personal exposure assessment, such as the works by Piedrahita et al. (2014), Dam et al. (2017), and Hojaiji et al. (2017). These sensors monitor a range of parameters, including toxic gases, VOCs, PM, temperature, and humidity, and have been developed using commercially available sensors. Their performance has been demonstrated in real-world scenarios. Some researchers have developed custom unobtrusive sensors for toxic gases and humidity and integrated them into PPE or gear such as respirators and face masks for improved respiratory safety and user comfort (Pang et al., 2018; Zhang et al., 2022). These research-stage monitors have the capability to provide real-time feedback displayed on smartphones and smartwatches, making them promising tools for personal exposure monitoring in workplaces. However, there are concerns regarding calibration stability and accuracy of exposure quantification.

In recent years, the design and performance of developmental-stage sensors have improved substantially owing to the rise of flexible electronics, advanced materials, nanotechnology, additive manufacturing, wireless communication, and advanced data analytics methodologies (Mamun & Yuce, 2019; Vijayan et al., 2021; Wei et al., 2024; Yuan et al., 2025). Fig. 3 shows the advanced sensors developed by Fahimi et al. (2019) for $PM_{2.5}$ (a, b) and Yoon et al. (2019) for VOCs (c) using one or more of these novel technologies. Fahimi et al. used a MEMS resonator based on mass sensing to develop a wearable PM sensor and showed its performance in comparison with a reference sensor (Fahimi et al., 2019). Similarly, Yoon et al. used a three-resonator sensor array based on capacitive micromachined ultrasonic (CMU) transducers and employed a pattern recognition ML method, such as principal component analysis (PCA), to achieve selective detection of multiple VOCs (Yoon et al., 2019). Moreover, researchers have used IoT architectures to enhance the functionality and connectivity of wearable air-quality monitors (Kodali et al., 2020; Palomeque-Mangut et al., 2022). These efforts have led to rapid progress toward advanced wearable sensor systems that can intelligently monitor individualized exposure in real time and predict unsafe conditions in workplaces.

5.3. Respirators and face masks as sensor platforms

Filtering facepiece respirators (FFRs) and face masks are among the most commonly used face-covering devices for creating barriers against airborne contaminants. FFRs are a type of PPE designed to filter out specific harmful aerosol particles, dust, mists, and fumes from the breathing air. Additionally, there are other types of respirators, namely elastomeric respirators and atmosphere-supplying respirators (ASRs), designed for specific hazardous conditions (Greenawald et al., 2021; NIOSH, 2025). Respirators must be approved by the National Institute for Occupational Safety and Health (NIOSH) to ensure adequate respiratory protection against specific hazards. However, face masks are not considered PPE as they do not necessarily provide respiratory protection

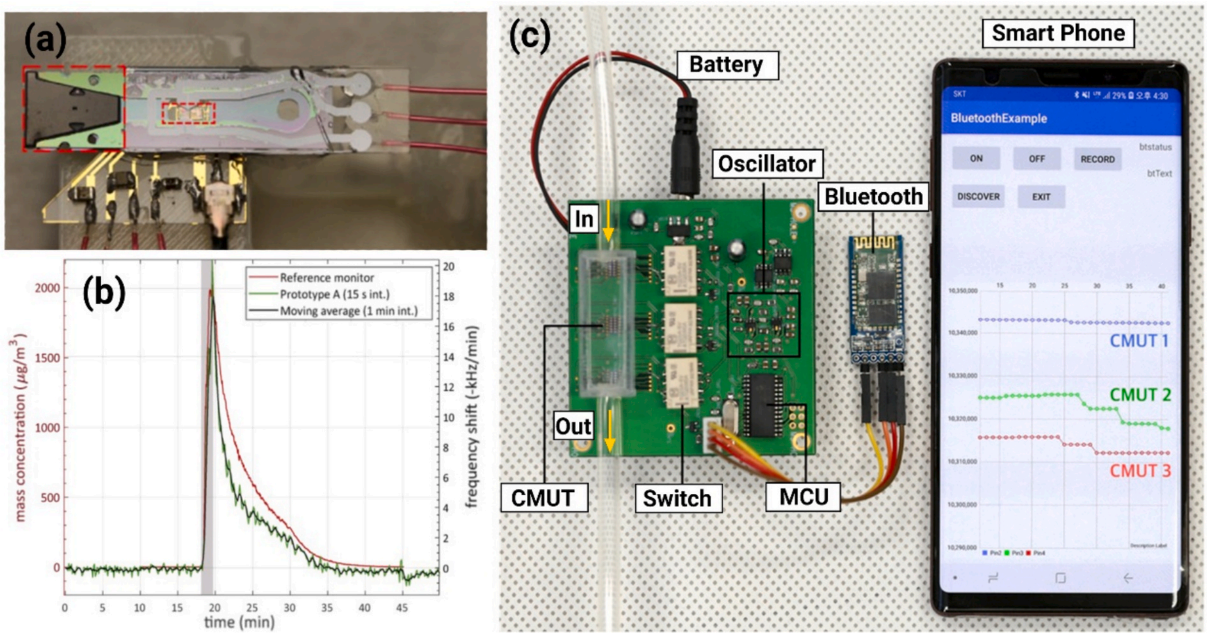

Fig. 3. Examples of advanced wearable or portable sensors for airborne contaminants. Panels (a-b) show a MEMS PM2.5 sensor prototype based on a mass-sensing resonator proposed by Fahimi et al. (Fahimi et al., 2019) for wearable applications and its performance relative to a reference monitor. Panel (c) is photograph of a portable sensor system for VOCs that comprises three CMU transducers (CMUTs) and a single read-out circuitry with the capability to wirelessly transfer data to a smartphone. This sensor system utilizes pattern recognition techniques and a phone application for improved performance and visualization. Panels (a) and (b) were reprinted from reference (Fahimi et al., 2019), with permission from Elsevier and (c) from reference (Yoon et al., 2019) under open-source licensing terms and courtesy of the authors.

to the wearer despite their widespread use. Recently, both types of devices have emerged as promising platforms for the integration of real-time sensors aimed at monitoring respiratory health, predicting external respiratory hazards, and evaluating their efficacy in real time (Lee et al., 2022). Because sensors embedded in these devices are located in a unique position within the breathing zone, monitoring both personal respiratory health and the surrounding environment can be highly effective. Additionally, workers in occupations such as healthcare, emergency response, and structural firefighting, where respirators or face-covering devices are mandatory, could particularly benefit from this approach, as it eliminates the need to carry additional wearables such as smartphones and smartwatches.

Although some efforts have been made before the COVID-19 pandemic to use these devices as a platform for wearable sensors, interest has significantly increased in recent years (Liang et al., 2025). An early example of integrating real-time sensors into respirators was by Sieber et al. (2011). They developed an electronics board with several features such as digital readout, on-board calibration, and lifetime prediction based on an electrochemical O_2 sensor output and integrated it into a closed-loop rebreather and tested its performance with divers. While the work focused on diving applications, it showed the feasibility of integrating active sensors into respirators in occupational settings. Currently, a few commercial products and several research-stage prototypes of sensor-integrated face masks and respirators are available. The commercial products have focused heavily on mitigating user discomfort, such as excessive moisture, breathing difficulty, and speaking difficulty. Lee et al. summarized some of these commercial products with special features such as sensing capability, actuation, and wireless connectivity (Lee et al., 2022). In addition, many researchers have proposed smart respirators and face masks that integrate various commercial or custom real-time sensors to advance the functionality of these devices (Aqueveque et al., 2022; Lin et al., 2022). While not all these devices were designed for a specific work environment, they hold potential for application across multiple workplaces (Pinnelli et al., 2024).

The parameters monitored by these integrated sensors include airborne pathogens and gases in the surrounding environment; physiological parameters; humidity, temperature, pressure, and the breathing air inside these facepieces; and the seal of these devices to the face (Hussain et al., 2023; Mirjalali et al., 2022). In 2022, Kim et al. demonstrated the monitoring of infectious diseases, environmental conditions, and wear status of user-supplied face masks by attaching conformable sensory electronics (Kim et al., 2022). Zhang et al. recently published work on innovative actuators attached outside a face mask for human-environment interaction (Zhang et al., 2025). This work demonstrated monitoring and visualization of air contamination levels, environmental temperature, and respiratory status in real time, providing real-time feedback to the user.

Researchers have also integrated biosensors dedicated to identifying biological agents into respirators and face masks. For instance, Mirjalali et al. (2022) reviewed various wearable sensors, focusing on the possible applications for early and remote diagnosis of COVID-19, including face masks and respirators as platforms for the sensors. In 2021, Nguyen et al. (2021) reported the development of a synthetic biology sensor integrated into a face mask for SARS-CoV-2 detection in exhaled aerosols. Their sensors were able to detect the virus and did not exhibit cross-reactivity with other human coronavirus strains (HCoVs). Similarly, Xue et al. (2021) proposed an intelligent face mask integrated with a high-density conductive nanowire array for monitoring exhaled coronavirus aerosols (Fig. 4(a)).

There is considerable work on monitoring the in-mask environments or the interface between these facepieces and skin for physiological parameters, breathing patterns, in-mask air quality, or seal integrity. In 2018, Pang et al. proposed integrating a wearable sensor into a medical breathing mask to monitor humidity in the environment inside the mask (Pang et al., 2018). They designed, built, and tested a wearable humidity sensor based on the resistance of a porous graphene network for respiration monitoring. The sensor was placed inside the mask and used to monitor humidity and extract breathing patterns. Similarly, Aqueveque et al. (2022) proposed an embedded electronic sensor inside a half-

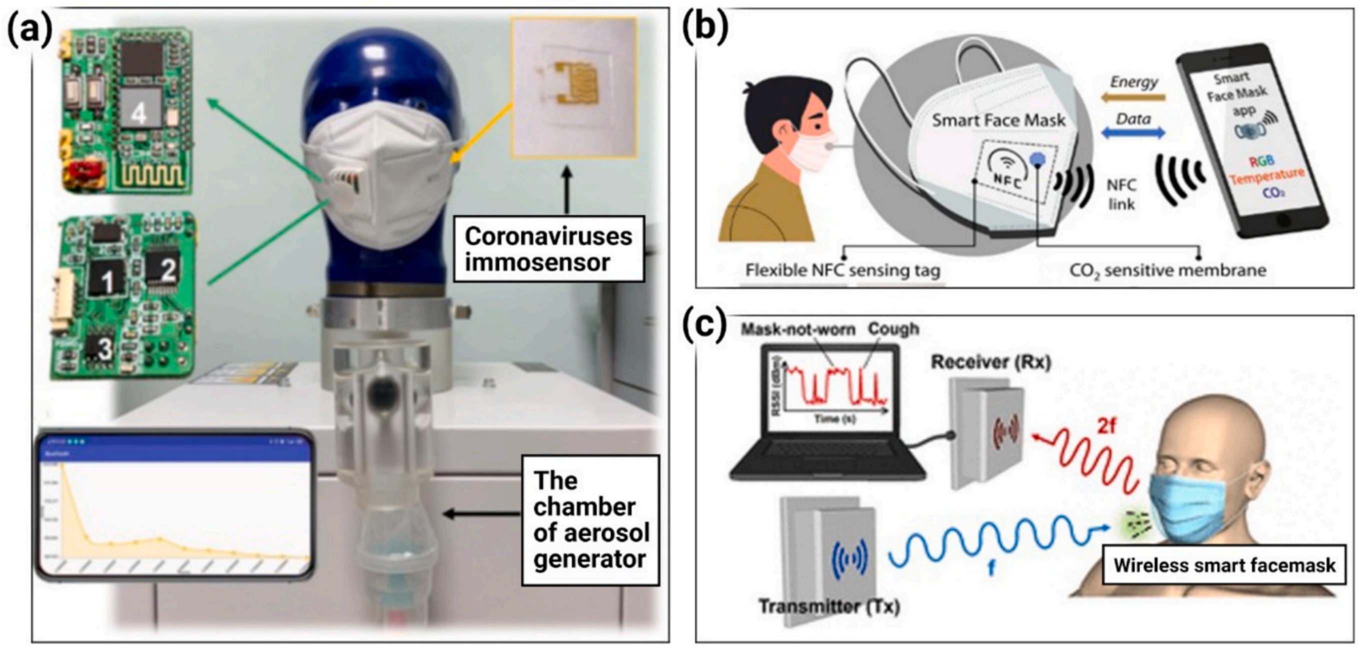

Fig. 4. Sensor-integrated respirators and face masks for real-time respiratory monitoring. Panel (a) is a nanowire-based sensor for detecting exhaled coronavirus aerosols (Xue et al., 2021). Panel (b) shows a sensor system to monitor CO_2 buildup inside a face mask (Escobedo et al., 2022). Panel (c) shows an RF-based wireless sensor for monitoring coughing events and mask-wearing status (Ye et al., 2022). Reprinted with permission from Elsevier (a), Springer Nature (b) and American Chemical Society Publications (c).

facepiece respirator to continuously monitor pressure, temperature, and humidity. They used these parameters to evaluate breathing rate, fit conditions, and filter clogging. They used commercially available sensors to build an embedded sensing system and Bluetooth to wirelessly transfer data to external devices and web servers. In 2021, Lazaro et al. (2021) reported the fabrication of a smart face mask by integrating wireless sensors capable of monitoring body temperature and breathing rate into a commercial mask. Bianco and Marrocco (2021) reported the integration of an RFID tag-based humidity sensor to measure humidity inside an N95 respirator and monitor wetness. The fabricated sensor was integrated into an N95 respirator and tested during normal activities and physical exercises. The sensors discriminated the wetness levels under these different conditions.

Studies have shown that prolonged use of FFRs and face masks can cause dizziness, headaches, hyperthermia, skin irritation, and discomfort (Akhondi et al., 2022) due to changes in the breathing environment, such as the levels of CO_2, O_2, pressure, humidity, and temperature (Escobedo et al., 2022; Johnson, 2016). The ability to monitor and quantify O_2 and accumulated CO_2 within the in-mask environment in real time can help alert the wearer to take necessary precautions. Casalinuovo et al. (2023) reported their preliminary results on a 3D-printed, low-cost face mask with integrated sensors capable of monitoring CO_2, humidity, and temperature inside the mask. The sensor was able to measure multiple variables simultaneously and transmit the acquired data automatically to a web terminal. Similarly, Escobedo et al. (2022) developed a smart mask with an integrated opto-chemical CO_2 sensor (Fig. 4(b)). This battery-free, opto-chemical sensor was able to transfer data to a mobile phone for display via a custom-developed application. There are efforts to integrate multi-parameter sensors inside these face-covering devices for comprehensive respiratory monitoring. For example, Ye et al. (2022) demonstrated a breathable and reusable face mask with an integrated wireless sensor for real-time monitoring of coughs and identifying the mask fit (Fig. 4(c). This RF transponder-based sensor was battery-free and lightweight and was integrated inside the face mask. This advanced face mask was able to simultaneously monitor mask wearing and coughing, while providing a barrier to external hazards. Another work reported by Adeel et al. (2022) demonstrated that various commercial face masks could be used as a platform for real-time sensors for face seal integrity of these devices along with several parameters, such as skin temperature, physical activity, and breathing patterns.

Table 3 summarizes some recent research and development efforts on using respirators or face masks to monitor various respiratory parameters, including external hazards, in-mask breathing conditions, and their face seal integrity. Continuous measurement of these parameters, both inside and outside the facepiece, is an innovative approach for enhancing respiratory protection in high-risk workplaces.

5.4. *Sector-specific applications*

5.4.1. *Mining*

Miners operate in high-stress and dynamic environments that may contain respirable dust (e.g., silica, coal, and other minerals), toxic gases (e.g., CH_4, CO, H_2S, CO_2, SO_2), and diesel aerosols (Laney & Weissman, 2014). Mine operations, whether underground or surface, may pose poorly ventilated atmospheres, thermal stress, and high humidity that can exacerbate respiratory health issues. Since respirable dust and gases may not be visible, diligent monitoring is essential to make informed decisions about donning respiratory PPE or stopping work to minimize risks. The confined nature of mining spaces poses challenges for fixed-area sensor deployment, making wearable sensing technology a viable alternative (Dempsey et al., 2018).

Efforts have been made to implement wearable real-time sensors by integrating them into PPE, such as hard hats, safety glasses, respirators, and clothing, to track respiratory hazards and physiological parameters among miners (Adjiski et al., 2019; Eizad et al., 2025; Mardonova & Choi, 2018). For example, NIOSH and Unimin Corp. developed a respirable dust assessment tool called Helmet-Cam, which combines a real-time aerosol monitor (belt- or backpack-mounted) with a helmet-mounted video recorder to analyze dust exposure (Cecala & O'Brien, 2014; Haas et al., 2016). This monitor can assess dust exposure and collect data while workers are on duty. However, the analysis of the data

Table 3
Examples of wearable sensors integrated into respirators or face masks for various respiratory parameters.

S. N.	Reference	Monitored parameter (s)	Sensor type and description	Additional features
1.	Xue et al. (2021)	Exhaled coronavirus aerosols	Nanoscale impedance immunosensor, conductive nanowire array	Miniaturized impedance circuit
2.	Ye et al. (2022)	Cough and mask-wearing	Radiofrequency harmonic transponder, silver nanowire	Battery-free, RF, wireless simultaneous monitoring
3.	Kim et al. (2022)	Biological and environmental samples (skin temperature, humidity, verbal activity, breathing pattern, fit status)	Accelerometer, capacitance sensor pad, air pressure sensor, temperature, humidity sensor	Simultaneous wireless monitoring, integrated with ML algorithms to decode the face mask position
4.	Kwon et al. (2025)	Humidity inside respirator and pressure on skin for self-fit adjusting	Resistive humidity sensor (laser-induced graphene) and capacitive (dielectric elastomeric sponge)	Self-fit adjustment, wireless, cloud storage capability, software application
5.	Escobedo et al. (2022)	CO_2 in inside the face mask	Opto-chemical; luminescence intensity; inorganic phosphor	Battery-free, custom smartphone application for wireless powering, alert management, and data visualization
6.	Kalavakonda, et al. (2021)	Airborne pathogens, PM	Laser scattering, piezoelectric actuator	IoT-enabled active mask, smartphone application
7.	(Li et al., 2023)	Multiple physiological and breathing parameters	Triboelectric nanogenerators (TENG)	Not integrated in respirator or face mask, self-powered, self-calibration, AI, data-mining algorithm, phone application
8.	Kuglics, et al. (2024)	Air Quality Index, Temperature, pressure, humidity	MEMS, resistance (Bosch BME680 commercial sensor)	IoT-capable wireless unit, attached at the inner and outer surfaces of a mask
9.	Fischer, et al. (2021)	Respiratory pressure (differential pressure), heart rate and oxygen level	Commercial sensors (MEMS pressure sensors – BME680 and LPS22HB, optical pulse oximeter – MAX30102)	Technology-garment co-designed smart mask, smart-sensing technologies inside the mask while maintaining its filter function
10.	Zhong, et al. (2022)	Pressure sensor, breathing condition	Piezoelectric film	Self-powered, wireless, compact readout circuit, cloud storage capability

collected needed to be performed later. Another device, the Personal Dust Monitor (Model 3700) developed by NIOSH and partners and commercialized by Thermo Scientific, is state-of-the-art portable monitor for real-time monitoring of coal dust (Colinet & Mischler, 2022; Thermo Scientific, 2025). Although these tools are recognized by NIOSH and the Mine Safety and Health Administration (MSHA), they are relatively bulky and heavy for use during work. Recently, low-cost, lightweight, and small-form-factor devices based on mass concentrations have been explored for dust and diesel exhaust (Hajizadehmotlagh et al., 2023). Parallel efforts include the development of smart safety helmets that integrate multiple sensors (e.g., temperature, humidity, and harmful gases such as CO and CH_4) with wireless transmission for near real-time analysis (Hazarika, 2016; Patil et al., 2023), enabling alerts when safety thresholds are exceeded. However, most of these monitors are still in their early stages of development and require further validation for long-term use in operational mines.

In addition to environmental hazard detection, there is growing interest in continuous monitoring of physiological parameters relevant to miners' respiratory health. For example, Ranjan et al. (2019) proposed a wearable health monitoring system wireless data transmission capability for underground miners, addressing challenges in tracking physiological data in underground mines. Similarly, there are ongoing efforts to develop smart masks for miners that integrate real-time sensors to monitor respiratory parameters (Wang et al., 2024). Utilizing such systems could enable early detection of respiratory stress and fatigue (which may be related to dust exposure) as well as gradual deterioration of lung health, the assessment of which is currently performed in periodic screenings. However, these systems remain at the conceptual stage or in early-stage field-validated prototypes. More recently, Liang et al. (2025) provided an extensive review of wearable systems for vital-sign monitoring in coal mines and emphasized the integration of IoT and AI platforms for predictive safety management in underground mines. Nevertheless, they noted that real-time physiological monitoring in mining remains far less developed than in other domains, such as in clinical settings. There is a need to integrate real-time respiratory hazard monitoring with physiological sensing into lightweight, durable wearable systems with wireless data transmission capabilities, validated under real-world mining conditions.

5.4.2. *Firefighting*

Firefighters operate under complex atmospheres (including PM, asphyxiants, and toxic gases), extreme heat, and low humidity, all of which threaten respiratory health (Bolstad-Johnson et al., 2000; Greven et al., 2012; Navarro, 2020). While acute smoke inhalation is a central concern, wearing respirators is not always practical during firefighting activities, such as wildland fire suppression and overhaul. Wearable sensors can support informed decisions during these activities by tracking hazardous exposure and physiological changes in real time (Shakeriaski & Ghodrat, 2022).

Designing and developing effective real-time monitors for firefighters is a complex task. There have been efforts to develop continuous monitors, portable or integrated with firefighting gear, using commercial or custom sensors to monitor various parameters (Coca et al., 2010; Edwards et al., 2005; Kelleher et al., 2018; Smith et al., 2014; Xu et al., 2024). Examples of wearable monitors for respiratory physiological parameters include the development and demonstration of smart vests and shirts by Coca et al. (2010) and Smith et al. (2014). Coca et al. evaluated a plethysmographic vest for monitoring heart rate, blood oxygen saturation, and ventilation parameters in a lab-based setup consisting of 10 subjects wearing standard firefighting ensembles (Coca et al., 2010). They found that the vest performed reasonably compared with standard equipment and suggested a field study. Similarly, Smith et al. developed a shirt with an integrated physiological status monitor and tested in simulated structural firefighting operations (Smith et al., 2014). The monitor performed well in tracking heart rate and respiratory rate during the simulated operations. In 2018, Taborri et al.

reviewed sensor-based systems for monitoring firefighters' physiological parameters, which identified that majority of studies were conducted in controlled laboratories or simulated firefighting environments (Taborri et al., 2021).

There have been some efforts to develop portable environmental sensors as well as integrated systems for exposure and physiological parameters for use in firefighting activities (Edwards et al., 2005; Kelleher et al., 2018). For instance, Edwards et al. (2005) assessed a custom-built real-time PM sensor during prescribed burns and highlighted that appropriate sensor design can reduce exposure. They concluded that an appropriately designed wearable sensor could help mitigate exposure during firefighting activities. In 2025, Pinnelli et al. (2025) field-tested a commercial non-intrusive multi-parameter sensor on 12 subjects during different activities for real-time monitoring of respiratory frequency, heart rate, and acceleration. An additional sensor recorded environmental temperature. A chest strap was used to mount sensors and collect data from participants. The study demonstrated that wearable sensors could reliably monitor physiological and environmental parameters during a firefighting situation. However, it is important to note that the study size was small, and not all parameters relevant to firefighting were considered (such as humidity and smoke were missing). There have been efforts to develop next-generation firefighting respiratory gear such as self-contained breathing apparatus (SCBA) with integrated monitors, to collect physiological and environmental data in real time (Kesler et al., 2015; Warner & Vargas, 2017). Technological maturation and longitudinal field validation of these efforts are necessary to overcome barriers, including sensor cross-sensitivity, stability, durability, and wearer comfort.

5.4.3. Healthcare

Healthcare workers (HCWs) and emergency responders are often exposed to intermittent respiratory hazards, including airborne pathogens, disinfectant vapors, and PM generated during clinical procedures (Zhu et al., 2018). Wearable environmental sensors that continuously monitor respiratory hazards can detect these hazards in real time, whereas physiological sensors are able to track respiratory health status, supporting early detection of respiratory illnesses and informed preventive actions (Clingan et al., 2021).

There has been a significant amount of work on wearable technologies to monitor respiratory health and detect diseases in clinical settings. However, most of these efforts have primarily focused on patients and personal wellness (Andrea, 2017; Karpiel et al., 2025; Vicente et al., 2024). Their application to respiratory safety and health of HCWs has emerged recently, especially during and after the COVID-19 pandemic (Clingan et al., 2021). In 2021, Clingan et al. designed a protocol to assess the feasibility of commercial wearable sensors (Fitbit Charge 3, TempTraq temperature patches) among HCWs to support self-monitoring and early detection of COVID-19. The protocol combined continuous physiological monitoring, a smartphone app, and self-reported daily mood and symptoms to enable early recognition of potential infection. Although the study was conducted in a single facility and was ongoing at the time of reporting the work, it highlighted the importance of sensor validation and user acceptability. Esmaeilpour et al. conducted a prospective validation study using consumer wearable devices to monitor respiratory physiological signals and detect common respiratory infections in HCWs (Esmaeilpour et al., 2024). A custom algorithm generated real-time alerts for possible infections, demonstrating the potential of wearable devices as early warning tools. However, the system had low positive predictive value, with many alerts triggered by non-infectious factors.

Some studies suggest that respiratory protection for HCWs could be enhanced by integrating wearable sensors into face coverings to monitor various respiratory metrics, as described in the previous section (Section 4.3). While the facepiece provides a barrier to hazards, the integrated sensors can provide real-time data on physiological signals, environmental parameters, the in-mask environment, and the structural integrity of the facepiece itself (Aqueveque et al., 2022). For example, Kim et al. evaluated the real-time performance of N95 respirators in a simulated healthcare setting under the OSHA Exercise Regimen (Kim et al., 2015). This study found that certain movements, such as looking up, down, and sideways, could contribute to respirator seal failure, highlighting the need for caution during patient care. Zhu et al. investigated the possibility of characterizing the respiratory flow of HCWs using wearable sensing devices attached to respirators, collecting data during simulated healthcare activities (Zhu et al., 2018). They suggested that these results could be useful in standards development and respirator design for improved respiratory protection. However, the sample size was small, and the selected tasks did not necessarily reflect typical healthcare practice.

More recently, Kim et al. (2024) reviewed research trends in detecting respiratory parameters using wearable sensors and utilizing ML technologies for an efficient healthcare solution (Kim et al., 2024). They also reviewed the application of wearable breath sensors for direct and continuous monitoring of biomarkers that could help early detection of respiratory diseases among HCWs and other populations. They noted the need for further advancements in sensor technologies and data analysis techniques to unlock the full potential of these sensors in healthcare practices.

5.4.4. Construction

Construction workers face diverse respiratory hazards that can include dust mixtures (e.g., wood, silica), metal fumes, solvent vapors, asbestos fibers, and gases (Boadu et al., 2023; Ringen et al., 1995). Exposure varies across tasks and locations, creating challenges in accurately identifying exposure types and quantifying their magnitude, which are key to selecting appropriate respirators (Ringen et al., 1995). Wearable sensors may aid decision-making by providing real-time data about exposure as well as respiratory physiological parameters (Ahn et al., 2019; Awolusi et al., 2018; Nnaji et al., 2021).

There have been several efforts to select, evaluate, and deploy wearable real-time sensors on construction sites or relevant environments (Salah Abusohyon et al., 2023; Shen et al., 2017). Aksut and Eren reported an approach for selecting available sensors, including respiratory sensors, for improving safety and health in construction sites (Aksüt & Eren, 2023). This study outlined a method to rank and select the available wearable sensors for construction safety and health. Shen et al. performed a case study on using commercial physiological status monitoring systems to track physiological parameters, including breathing rate and heart rate, of two construction equipment operators on a construction site (Shen et al., 2017). They compared breathing rates across various activities and rest conditions, which could inform respiratory health. However, the study duration was limited and lacked comparison with standards. An example of exposure monitoring is a recent effort by Abusohyon et al., who demonstrated continuous and non-invasive monitoring of hydrogen peroxide in exhaled breath for construction workers using a custom-designed smart mask incorporating a nanostructured electrochemical sensor (Salah Abusohyon et al., 2023). Though this study was in a laboratory setting, they claimed that the proposed system could be employed for monitoring respiratory-related risks in construction and other industries. Similarly, Forsyth et al. proposed an indirect way of assessing CO exposure among construction workers by integrating a pulse oximetry sensor into a construction helmet to monitor blood gas saturation levels (Forsyth et al., 2012). The study was conducted among 10 subjects in simulated construction tasks without exposing participants to high CO concentrations. The authors mentioned that the results of this initial study were promising but also noted that further work is needed in more complex scenarios. In 2025, Lee reported on the integration of multiple sensors in safety workwear for respiratory protection and other functions on construction sites (Lee, 2024). The study was, however, limited to prototype assessment in a simulated environment. It is important to note that thorough field validation is required before recommending deployment in a dynamic, multi-hazard environment like construction.

While several efforts were focused on assessing or designing wearable sensors for applications in the construction sector, there are limited efforts to understand users' comfort and acceptance. Nnaji et al. studied the preferences of construction workers among various wearables, which indicated that smartwatches, smart hard hats, and smart vests were the most preferred wearables (Nnaji et al., 2021). They pointed out that construction workers may be reluctant to use wearable sensors due to privacy concerns and suggested the need to develop systems to address these concerns (Nnaji et al., 2021). For successful deployment, validating the performance in the field and addressing users' concerns regarding data privacy seem to be major challenges.

5.4.5. Oil and gas

Workers in the oil and gas industry, especially at production sites, are routinely exposed to a range of respiratory hazards. These include toxic gases such as H_2S and CO, flammable hydrocarbon vapors, VOCs, oxygen-deficient environments, diesel PM, and crystalline silica (Keerthi Narayanan et al., 2023; Witter et al., 2014). The confined spaces and dynamic work environments in production wells further increase respiratory health risks for workers during various activities. Modern wearable sensors with the capability for continuous monitoring and real-time feedback can enable early detection of respiratory hazards and proactive risk management in the oil and gas sector (Oil Price API, 2025; Moon & Ju, 2024).

There exist several personal gas detectors such as MSA ALTAIR io™ 4 (MSA Safety, 2025), ION Science personal gas detectors (Ion Science, 2025), and Blackline Safety gas sensors (Blackline Safety, 2025) to monitor toxic gases (including H_2S, CO, and SO_2) and VOCs in the oil and gas industry. These detectors provide effective real-time alerts for single-gas hazards to the wearer and in some models, wireless connectivity for supervisor notification. However, they have limited capacity to address simultaneous exposure to multiple hazards. Additionally, many commercial units do not support continuous recording of exposure data over long shifts or real-time data transmission without integration with third-party communication systems. Novel research prototypes that integrate multi-parameter wearable sensors with advanced communication protocols and AI/ML algorithms are expected to overcome these limitations by enabling more comprehensive monitoring and real-time feedback (Oil Price API, 2025; Wanasinghe et al., 2021).

Kuijpers et al. reviewed the literature on applications of various wearable technologies for assessing multiple exposures among oil and gas workers (Kuijpers et al., 2021). They concluded that there is a relatively small number of studies focused specifically on this occupation. However, several personal sensors developed for other industrial sectors could be adapted for personal exposure monitoring in this industry. The authors also highlighted key challenges, including multi-parameter sensor readiness, limited applied research, including designs for longitudinal studies in the oil and gas sector, and the need for certification for use in potentially explosive environments. Another recent review examined smart PPE that integrated wearable sensors, IoT, and AI for monitoring environmental hazards and physiological parameters among oil and gas workers (Smart et al., 2025). The authors cited case studies and industry reports from other sectors, highlighting the limited number of studies focused specifically on oil and gas operations. This review emphasized the need to incorporate AI, advanced materials, and connectivity to develop novel wearable sensors and smart PPE for improved safety in the oil and gas sector.

There are many promising sensor devices for simultaneous monitoring of multiple exposures and respiratory physiological parameters in the oil and gas sector (Lin et al., 2022; Patel et al., 2022; Yin et al., 2024). Binajjaj et al. designed a wearable gas sensor network system for oil and gas industry workers that measured CO and CH_4 exposure and sent warning messages to other workers (Binajjaj et al., 2018). However, field-validated studies that fuse continuous monitoring of chemical species and physiological parameters remain limited (Lin et al., 2022; Patel et al., 2022).

5.4.6. Cross-sector and general applications

The industry sectors discussed above are representative sectors that pose high risks to workers' respiratory health. In addition, there are many other industries such as manufacturing, welding, and agriculture that contain several respiratory hazards. Many sensor systems developed for one industry setting can be employed in other sectors, with or without further modifications. Additionally, there are efforts to develop general sensor systems for applications in multiple industries. For example, Campero-Jurado et al. (2020) proposed and developed an AI-powered multisensory smart helmet by incorporating several sensors, including those for environmental and physiological parameters. The system incorporated advanced analytics methods and real-time alerting capability based on the sensor output, which could help reduce exposure in high-risk sectors such as mining, construction, manufacturing, and emergency response. However, the reported system was at the prototype stage and required broader field validation. As described in the previous section, there are several studies that proposed integrating real-time sensors into respirators and face masks for respiratory protection in various occupational settings. Pinnelli et al. (2024) integrated two temperature sensors, one inside and one outside, into a filtering facepiece face mask to develop a real-time respiratory monitoring system for various work environments. This demonstration study compared the performance of the sensor configurations on monitoring workers' respiration rate across different settings. While the system was promising for several sectors, the authors highlighted the need for application-specific sensor selection and regulatory considerations. An example of a standalone sensor system attachable to personal gear is the wearable monitor developed by Tryner et al. (2023). They developed a small, wearable monitor for PM and VOCs that could be attached to personal gear and field-tested among employees at an agricultural facility, successfully tracking personal exposures under varying conditions. The prototype was lightweight and practical for exposure assessment in multiple industry settings, but its low sampling rate and reliance on laboratory analysis of filters and sorbent tubes limit deployment at lower PM concentrations and increase costs. Validation to the reporting date was limited to a single occupational setting.

These case studies illustrate that while wearable respiratory protection technologies are increasingly applied across diverse industries, most remain at prototype or pilot-testing stages, with limited large-scale deployment in real-world conditions.

6. Challenges and opportunities

Advancements in wearable sensors have been possible due to rapid growth in several enabling technologies, including materials science, device engineering, fabrication, wireless communication, feedback technologies, and data analytics. Integration of these devices into wearables such as smartphones, smartwatches, and protective equipment and clothing / textiles has significantly enhanced their usability in diverse occupational settings. Despite these advances, there exist multiple barriers to adopting these technologies as reliable tools for respiratory protection across workplaces (Schall et al., 2018). Below is a summary of key challenges and areas for advancement to support widespread adoption of these devices.

6.1. Technical challenges

Most state-of-the-art wearable sensors have been evaluated under laboratory or simulated work environments, while prototype-state sensors remain at an early stage. Evaluation of these sensors in occupation-specific scenarios and the development of standard testing protocols and safety frameworks are crucial for their scalability and practical use. Inconsistent device performance and limited validated references are among the major challenges in developing these standards and safety frameworks.

Developing efficient, reliable, durable, and user-friendly wearable devices requires overcoming several key challenges, including miniaturization, cost reduction, power management, and data security. State-of-the-art monitoring systems typically rely on single-parameter sensors, creating complexity for a comprehensive assessment of personal respiratory health and exposure. This approach often results in bulky, power-hungry, and costly systems. In addition, power and battery requirements at sensing locations restrict long-term field deployment and can reduce wearer comfort due to added weight, bulkiness, and risks associated with batteries. Higher manufacturing and material costs further increase overall cost. Although advances in wireless communication protocols have made these devices wearable and more IoT-compatible, secure and reliable data transmission remains a challenge.

It is important to note that common placements (wrist, helmet, belt, armband, backpack, smartwatch) for general wearable sensors may not reflect breathing-zone exposures and potentially limit relevance for respiratory protection. Embedding sensors into protective gear such as respirators and face masks or attaching them to clothing near the breathing zone is a viable option, but this raises several challenges, including airflow management, discomfort, obtrusiveness, and regulatory compliance. Validated references and standardized test protocols to evaluate the performances of these embedded devices are limited or lacking. Finally, integration of wearable sensors with other workplace technologies, including IoT, AI, and mobile platforms, is essential for developing intelligent safety systems.

6.2. User acceptance and regulatory compliance

Adoption of wearable sensors depends on user comfort, perceived benefit, and cost. In the survey by Schall et al. (2018), respondents estimated that employers would be happy to spend less than $75 per person per wearable. Furthermore, many portable and wearable sensors add burdens to users, especially in highly demanding occupations. For example, even a small increase in the weight of firefighters' gear could compromise mobility (Son et al., 2022; Xu et al., 2024) and integrating electronic modules into respirators or face masks could impede breathability. In addition, sensors must be designed to avoid any distraction or interference to regular tasks, especially in high-risk or dynamic work environments. There are also concerns about data security and users' privacy.

Regulatory compliance is critical in applying new technologies, including wearable sensors discussed in this paper, for workers' safety in workplaces. In addition, standardized testing and reporting frameworks, secure data transmission, privacy protection, and clarity around data ownership and legal responsibility are essential for ethical and compliant deployment in occupational settings.

6.3. Opportunities

Potential directions for future research and development are guided by the challenges discussed above. Addressing these challenges requires multifaceted efforts involving academia, industry, and government agencies.

A key priority is the development of multi-parameter sensor arrays on a single substrate for simultaneous monitoring of physiological and environmental variables, which can enable comprehensive analysis while reducing device cost, size, and weight. The incorporation of advanced data-analysis techniques, including AI and ML, is another avenue for improving the functionality, interpretability, and usability of these systems. The research on using nanomaterials, flexible materials, and stretchable materials along with advanced manufacturing technologies, such as MEMS, could create conformal and miniaturized devices that enhance wearability and unobtrusive monitoring. Further opportunities lie in developing self-powered or wirelessly powered devices with inherent wireless data transfer capability, such as passive surface acoustic wave (SAW) sensors (Devkota et al., 2017), which could significantly reduce circuit complexity and improve wearer acceptability. These devices can also be designed for multi-parameter sensing, thereby further simplifying the sensing system (Devkota et al., 2019).

Another critical area of future study involves optimizing sensor placement, including integration with PPE, protective clothing or other workplace gear to monitor target parameters. The placement should not impact or cause distraction, nor should the sensor placement impact the protection offered by PPE or protective clothing. Similarly, research into secure telemetry methods, edge analytics, and regulatory frameworks for data use is needed to ensure data security and user privacy. Another emerging direction involves the design of effective feedback mechanisms tailored to specific industries to provide real-time, actionable alerts.

For field validation and calibration, adopting established instruments or samplers as reference standards for benchmarking is essential. Additionally, collaborative initiatives among researchers, industries, and regulatory agencies will be vital to accelerate occupation-specific field validation, define performance metrics, and establish standardized testing protocols, laying the groundwork for regulatory compliance as the technology matures. Finally, applying ML algorithms and AI-assisted tools could be a novel opportunity in accelerating progress across all aspects of wearable sensor research and applications, including conceptual design, materials selection, data analytics, and real-world deployment for occupational respiratory protection. At the same time, ethical practices in using these tools are equally important for successful deployment of the wearable sensors.

7. Summary

The review synthesized findings from a diverse set of scholarly sources, including technical reports, original research articles, and review papers focused on the applications of wearable sensors for workplace respiratory safety. Selected studies addressing applications for air-quality, in-mask micro-environment, and facepiece status assessment and human-centric monitoring were examined, with particular emphasis on parameters directly related to respiratory parameters. Special attention was given to the emerging use of respirators and face masks as platforms for integrating wearable sensors in occupational deployments. Finally, we discussed key challenges and outlined potential directions for future research and development. Our analysis indicates that real-time and continuous monitoring of respiratory parameters in occupational settings has received limited attention. Additionally, interests in monitoring conditions within respirators and face masks and using them as novel platforms for wearable environmental sensors have surged since the COVID-19 pandemic outbreak. Despite major technological advances in wearable sensors, their applications for respiratory protection in occupational settings will require coordinated and extensive efforts spanning sensor design optimization, field validation, standards development, and regulatory compliance.

CRediT authorship contribution statement

Jagannath Devkota: Writing – review & editing, Writing – original draft, Data curation, Conceptualization. **Hom N. Sharma:** Writing – review & editing, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Disclaimer

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