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REVIEW ARTICLE

Assessing respiratory complications by carbon dioxide sensing platforms: Advancements in infrared radiation technology and IoT integration

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Abstract Respiratory illness demands pragmatic clinical monitoring and diagnosis to curb numerous fatal diseases in all aged groups. Due to the complicated instrumentation, long amplification periods, and restricted number of simultaneous detections, present clinically available multiplex diagnostic technologies are difficult to deploy the onsite diagnostic platforms. The futuristic assessment of medical diagnosis eases the respiratory monitoring using exhaled breath, due to the simple and comfort non-invasive detecting techniques. Carbon dioxide (CO_2) stands as a promising biomarker and has been identified in exhaled breath samples that distinguish different respiratory issues. State-of-the-art CO_2 gas sensing strategies are recognized with the growth of modern telecommunication technologies for real-time respiratory illness monitoring and diagnosis using exhaled breath. The presented article reviews the existing CO_2 gas sensors and their developments towards medical applications. With that, the advancement of infrared (IR) CO_2 gas sensors with distinguished light and sensing properties in detecting respiratory disorders are overviewed. The development of optimal CO_2 gas sensing strategy incorporated with Internet of Things (IoT) technology is over-reviewed. The hurdles encountered in the existing research and future preference with

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real-time CO_2 monitoring and diagnosing respiratory disorders with the advancement attained in IR sensing technology and IoT networking are highlighted.

1. Introduction

Chronic respiratory diseases are the leading cause of illness for all ages, providing ~ 3 million deaths worldwide. Among that, children, and aged population, consisting about 240 million are suffering from the respiratory disorders ("WHO-Chronic respiratory diseases," n.d.). Asthma, chronic obstructive pulmonary disease (COPD), respiratory infections are the common respiratory illnesses, caused by variety of abnormalities experienced in human airways. However, the clinical symptoms for these respiratory disorders are similar, and giving a tough time for medical personnel in diagnosing the specific respiratory disease. In the effort of diagnosing respiratory diseases at an early stage, several invasive methods were developed and practiced in clinical conditions. Endotracheal aspiration, transtracheal needle aspiration, and specimen brush are the traditional invasive methods, which are then upgraded to blood and urine sample analyses (Nicolò et al., 2020). Although the methods have been proven in the accuracy of disease diagnosis, it troubles the medical personnel and patients to perform the invasive diagnostics. It is not only discomfort to patients, but also causes difficulties to diagnose the disease outside of medical domains. Thereafter, the advancement of diagnosing respiratory illness through exhaled breath was developed. Exhaled breath is the most accessible sample for respiratory disease diagnosis, which effortlessly released by humankind. Non-invasive respiratory disease diagnosis through exhaled breath offers convenient clinical monitoring, a very low infection risk, and it is an easily repeatable method. In that followings, numerous strategies were developed in monitoring and diagnosing respiratory diseases through exhaled breath, which consist of ~ 250 volatile organic compounds (VOC), pulmonary exchange gases, water vapor and variety of trace compounds (Mafarage, 2021). Among that, carbon dioxide (CO_2) is one of promising biomarkers as a gas. The varied expiration levels enable to evaluate the systemic metabolism, ventilation, and pulmonary faultiness, provides the information for diagnosing the respiratory and pulmonary disabilities (Macias et al., 2021; Pan et al., 2020).

Sensors with the ability to detect CO_2 in medical applications with high accuracy and rapid readouts are still critical. Several types of gas sensors are introduced and incorporated with multiplexed materials to capture CO_2 gas and interpret the respiratory conditions (Yang et al., 2015). While useful, the establishment of these sensors to greater heights are hindered by the interferences caused by humidity, water vapor and the hard wares equipped in the sensing system. Regarding that, series of developments are conducted with variety of CO_2 gas sensors, which have improved and enhanced CO_2 gas monitoring access for identifying respiratory disorders (Rezk et al., 2020). The distinguished light absorption properties of IR technology have an edge towards the gas sensing due to the accuracy, high sensitivity, and selectivity, with the specific IR regime in the spectrum (Fleming et al., 2021; Glöckler et al., 2020; Liu et al., 2021). There are several IR based exhaled breath analyzers, which are commercially available, and mainly for capnography application. Among these, non-dispersive IR (NDIR) sensor is found to be prominent for CO_2 gas sensing as it gives a straightforward absorption, without the need for optical dispersion. NDIR gas sensors have gained high interest in the current decade as they are widely applied in oil and gas industries, automobile industries, coalmines, etc. The primary objective of incorporating NDIR CO_2 gas sensors in respiratory healthcare is acquiring high accuracy readout, with low detection limit and rapid responses (L. Zhou et al., 2021).

With the growing demand for portable breath diagnosis, the growth of employing CO_2 gas sensors in medical health has been giving prospective outcomes in disease diagnosis and monitoring (Aliverti, 2017; Lokman et al., 2021). For years, numerous review articles have summarized various CO_2 gas sensing methods from the perspective of clinical conditions. Comprehensive overviews of various kinds of gas sensors for medical diagnosis are presented, and clearly showed the shift from conventional, rigid electronics to flexible sensors (Duan et al., 2022; Tai et al., 2020). Although the above reviews have successfully summarized the recent advances in gas sensing analyses, it is difficult to find an extensive review that focuses on exhaled CO_2 gas sensing from human breathing conditions using IR CO_2 sensor, with its integration with current Internet of Things (IoT) state-of-art. Several reviews have summarized breath analysis using exhaled gases, yet the research progress on non-invasive exhaled CO_2 gas using IR technology and its impact for clinical monitoring respiratory conditions are still at preliminary state (Duan et al., 2021). With the regard, the review discusses the modern technologies associated with CO_2 gas sensing from exhaled breath, precisely for monitoring and diagnosing respiratory illnesses. The breakthrough of IR CO_2 sensor is overviewed in conjunction to the growing sensor technology. As it meets the current trend, the prospective vision of IR CO_2 gas sensors incorporation with IoT technology is presented. The challenges and potential of IR CO_2 sensors are discussed to encourage the modern future of respiratory care with IR functionalities and IoT technologies.

2. Acute respiratory responses to altered carbon dioxide

The mainspring of effortless CO_2 exhalation from human body is the partial pressure of CO_2 (pCO_2) between the alveolar membrane (40 mm Hg) and bloodstream (46 mm Hg), which is ~ 6 mm Hg in difference. The variation in pCO_2 is relatively small, yet the gas exchange is rapid. The solubility of CO_2 is good compared to oxygen (O_2), which ensures effortless gas exchange during cellular respiration. Disruption in CO_2 level instantly affects the gas exchange and cellular respiration rate in the human body. If the CO_2 level dropped, hypocapnia happens, where the cerebral vasocontraction causes cerebral hypoxia, which leads to high respiration rate, muscle cramps, and dizziness. When the CO_2 level is raised, hypercapnia happens, which increases the systolic blood pressure and leads to abnormalities in respiration. The physiologic change in CO_2 is well adapted by human body to detect and rectify the abnormalities, with exclusion from the external domain influence (Cobb, 2021). A healthy human being has evolved excellent sense of detection and response to counterpart the endogenous CO_2 level and maintain the homeostasis. Unlike acute state, mild physiologic states and responses are asymptomatic, which may not be recognized and experienced by a person with abnormal respirating condition. Such abnormalities may lead to acute respiratory illness when it is not treated at its initial stage. As a part of physiologic response, the respiratory organs response to the high CO_2 by generating specific gene expression and signal transduction with specific sequences to overcome the high pCO_2. Such response is recognized as a significant signal in diagnosing respiratory illness through the level of pCO_2 in human (Cummins et al., 2020).

Sharp increase of pCO_2 in bloodstream increases the pCO_2 in cerebrospinal fluid in the brain and spinal cord. The increment in pCO_2 increases the H^+ concentrations in the fluid. The decrease of pH in the cerebrospinal fluid causes acidification and unable to neutralize due to the absence of red blood cells. Such condition is identified as respiratory acidosis, which caused by alveolar hyperventilation and eventually results in acute respiratory illness, such as asthma, COPD, and emphysema (Huttmann et al., 2014; Pan et al., 2020). Asthma is one of the severe respiratory illnesses afflicted by patients with high pCO_2 or known as hypercapnia. The elevated CO_2 gas in arterial capillaries complicates the alveolar gas exchange and causes asthma. The high CO_2 acts as significant gaso-signal to determine the severity of asthma and other chronic respiratory illness. High pCO_2 is reported in approximately 10–30 % of patients rushing to emergency units with abnormal and severe respiratory rate. According to medical data, the pCO_2 in asthmatic patients stands from 200 mmHg and goes up to 300 mmHg, which is categorized as a severe acute asthmatic condition. The range in pCO_2 is unpredictable with any criteria such as gender, age, and external domains. It is solely representing the severity in airflow obstruction, which indicates the asthmatic condition (Xiao et al., 2020).

High pCO_2 has shown a series of symptoms and consequences to human respiratory condition. Fig. 1 shows the possible condition of lung and its organelles with high pCO_2. Besides that, factors such as unhealthy lifestyle and environmental influences could elevate the pCO_2 from the developed chronic diseases, such as bronchitis, emphysema, and pulmonary edema. According to medical experts, asthma do not stop its consequences at the respiratory organs but extends its severity to other main organs such as brain, heart, and spinal by causing cardiovascular illness, brain hemorrhage and cerebral edema (Adamkiewicz et al., 2020). A study conducted by Stow and team at Australian ICU from 1996 to 2003 reported the significant effect of high pCO_2 in asthmatic patients. The study proved that non-surviving asthmatics who were not supported by mechanical ventilation showed prominent increase in pCO_2, but negligible variation in the arterial oxygen level. The study has emphasized the importance of monitoring pCO_2 than arterial oxygen level in diagnosing severe respiratory illness (Stow et al., 2007).

3. Carbon dioxide sensing strategies

Expert's effort in producing advanced gas sensing tools in response to state-of-the-art global technology and raising health issues with unhealthy lifestyles is never ending. Exhaled CO_2 measurement by evaluating pCO_2 and end-tidal CO_2 ($EtCO_2$) is notable for non-invasive diagnosis of acute respiratory illness (Ghorbani and Schmidt, 2017). The emerging method of interest is the non-invasive CO_2 measurement from human breath for assessing the metabolic state of human respiratory condition and prompt determination of airway obstruction and illness. The classic issue experienced with non-invasive CO_2 measurement tool is the interference from humidity. Several pretreatment techniques to eliminate breath humidity have been handled in literature. Unfortunately, it adds drawbacks to the cost of product technology and restricts the extensive usage of measuring tool from clinical settings (Zhao et al., 2014). Regarding that, researches are introducing variety of CO_2 sensing tools with variation in method of CO_2 collection, analysis, and output presentation, inclusive of relatively simple, inexpensive, rapid, and user-friendly tool at clin-

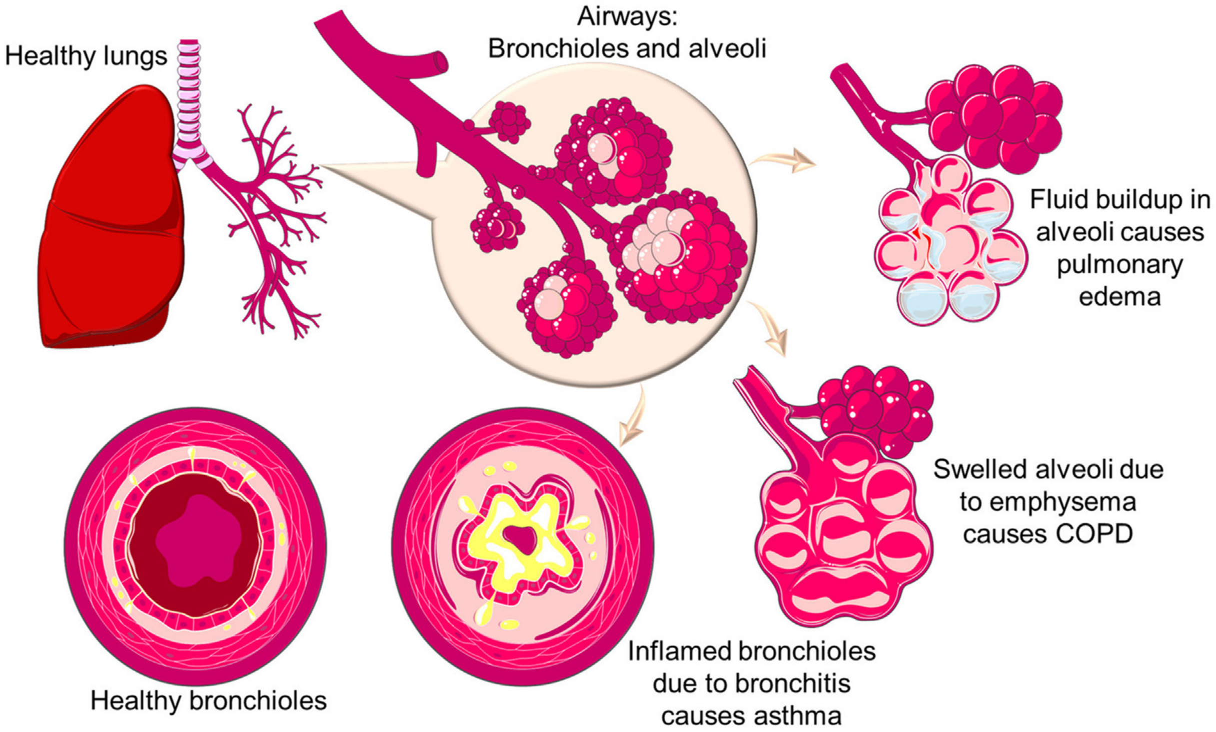

Fig. 1 Illustration of healthy lung airways and its unhealthy states, which lead to several respiratory illnesses such as pulmonary odema, COPD, and asthma.

ical settings and home environments. The section below overviews the types of CO_2 sensors developed for diagnosing respiratory illness through human breath.

3.1. Electrochemical sensing platforms

The electrochemical sensor has its own breakthrough as a promising gas sensor. Electrochemical sensing platform is developed using the oxidation–reduction reactions occur at the sensing electrode. The CO_2 gas to be detected undergoes oxidative reaction at the anode, as the reductive reaction of carrier gas occurs at the cathode. Ions are transferred to the anode through an electrolyte and electrons are transferred to a cathode through an external circuit, resulting in a reduction. As the current flowing through the external circuit increases in proportion to the CO_2 gas concentration, the concentration is evaluated by monitoring the current value (Hanafi et al., 2019; Khan et al., 2019). Fig. 2ai shows a schematic diagram of CO_2 electrochemical sensing using quinone as the redox-active carrier. As an alternative route to boost the CO_2 kinetics, the chemistry of redox-active carriers is modulated for undergoing proton coupled electron transfer (Fig. 2aii). A pH swing route is generated, where the acidic pH at the anode and alkali pH at the cathode increases the electron transfer with the high H^+ ion movements (Sharifian et al., 2021). The reliability of electrochemical sensors for CO_2 gas detection is propitious, as the sensors operate at a broad range of temperature (-30 to 1600 °C), without demanding additional heating. The primary advantages of electrochemical sensors for ambient gas monitoring are having high resolution with low energy output, sensitive detection at ppm levels, an inexpensive technique, and showing good selectivity and repeatability outputs. But these sensors also suffer from limited measurement accuracy and problems of long-time stability (Aroutiounian, 2020). The superiority of electrochemical sensors at high temperature operations allowed its vast application in industrial gas sensing and less applied in health monitoring (Khan et al., 2019). Even so, there are several works reported in applying electrochemical system for respiratory gas sensing. Lee et al. reported a solid-state electrochemical micro-CO_2 sensor using complementary metal oxide semiconductor (CMOS) with microelectromechanical (MEM) technique. Due to their stable ionic conductivity and electrochemical stability, Li_3PO_4 thick film was utilized as solid electrolyte and Li_2CO_3 thick film was procured for sensing material, where the materials were structured as bridge type micro-heater, as shown in Fig. 2b. The performance of sensor was tested with carbon dioxide gas, which showed good value of $\sim$ 50 mV and a low power consumption at 59 mW (Lee et al., 2017). In another study, a relatively simple potentiometric CO_2 measuring sensor was developed using electromotive force (EMF)-based electrode sensing material and a solid-state electrolyte. Fig. 2c shows a CO_2 detection sensor with an auxiliary phase between sensing electrode and electrolyte. The sensing material has sodium ions (Na^+) and the NASICON electrolyte has sodium-ionic mobile carriers, which poses good ionic conductivity and high tolerance for doping with aliovalent cations allows to tune the crystal phase and transport properties. The gas samples diffuse across the

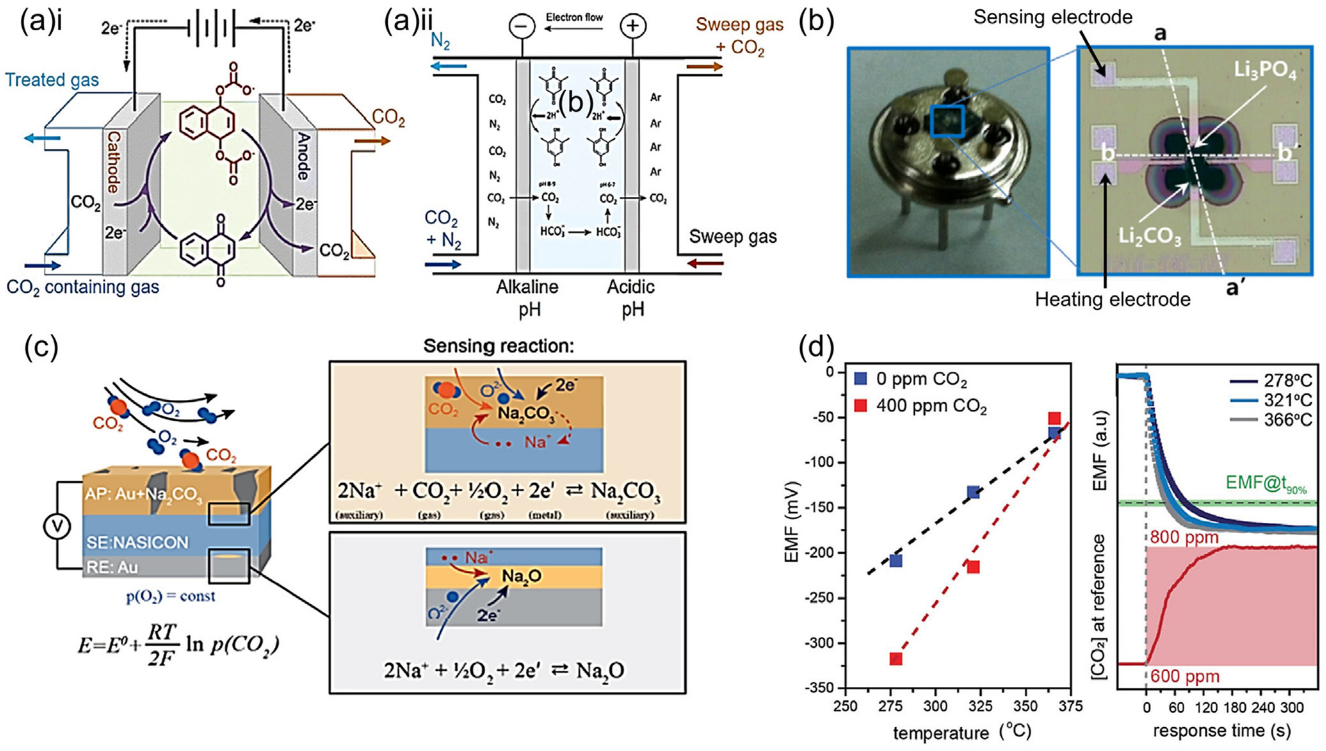

Fig. 2 Electrochemical gas sensing strategies. (a) Electrochemical CO_2 sensing using (i) quinone redox active carrier and (ii) proton coupled electron transfer system Reproduced with permission (Sharifian et al., 2021) Copyright 2018 RSC. (b) Digital and cross-sectional images of electrochemical gas sensor developed using lithium phosphate as solid electrolyte. (c) Electrochemical gas sensors developed with NASICON as solid states electrolytes. (d) EMF against the temperature for selected CO_2 concentrations and its response time Reproduced with permission (Struzik et al., 2018) Copyright 2018 WILEY-VCH.

auxiliary phase in a range of 60 s response time and the kinetic changes were read and evaluated through Nernst equation (Fig. 2d). The study demonstrated the possible outcomes of electrochemical potentiometric CO_2 sensors, which revealed a reduced energy consumption sensing system with a fast response time (~60 s) and low CO_2 concentration (~200 ppm) (Struzik et al., 2018). The reported works were encouraged for CO_2 respiratory gas monitoring, which endure thermal and structural stress with the essential modifications in the electrolyte systems.

3.2. Sol-gel system

Sol-gel method is one of most welcomed mechanism in material science, with its diversity of consuming multiple materials at low cost and simplified system. It substitutes the traditional method of developing glass or other materials, concerning its operation at variable conditions (Dansby-Sparks et al., 2010; Lalam et al., 2020). There are several unique advantages of applying sol–gel method in gas sensing. The generation of highly sensitive material using several recognition elements, and stabilizers results in a stable material, which is not disrupted by external domains. Moreover, additional techniques as doping and grafting engulfs the sol–gel materials to yield a functionalized and precise system (Bahar et al., 2014; Nivens et al., 2002). Unlike the common doping process, sol–gel followed doping enables the formation of thin layer or controlled pore size particles in the nanoscale range (Mujahid et al., 2010). Thin sol–gel films have been approached in developing sol–gel based gas sensors for detecting CO_2 and applied in the growing demand of gas phase detection. In a recent work, sol–gel technique was implemented in producing chitosan integrated with inorganic nanomaterials for CO_2 gas sensing. A chitosan/calcium aluminosilicate hybrid nanocomposite was synthesized using sol–gel method to detect CO_2 at ambient conditions. The sol–gel based gas sensing was evaluated through the change in absorption bands and crystallization degree of hybrid materials, which is reflected in the dielectric characteristics of the system upon the presence of CO_2 gas. The uniqueness of the hybrid material-based sol–gel gas sensing system is evidenced through the dielectric behavior and the sensitivity for CO_2 detection with these nanocomposites (Abou Hammad et al., 2019).

3.3. Metal oxide-based sensors

Numerous research has reported on using metal oxides sensing systems in detecting CO_2 in exhaled breath samples. Metal oxide gas sensors are well-known as chemo resistive sensors in detecting gaseous by evaluating the changes in the electrical resistance as the concentration of gas molecules alters (Marzorati et al., 2021; Righettoni et al., 2015). The sensors have gained much attention for their advantages in integration with microchips, and excellence in exhibiting great stability and reusability. Metal oxides incorporated with gas sensors absorb the gas molecules and induce electron mobility onto the metal oxide conduction bands. The electrons transformation alters the carrier charges in the metal oxide surfaces resulting in effective readouts in term of resistance and conductivity of the system (Vajhadin et al., 2021). With the advancement in novel nanomaterials, metals oxides are hybridized with various nanomaterials, nanocomposites, inorganic polymers, and carbon nanostructures to attain a desired gas sensing system with delivering an excellent analytical performance of a gas sensor, in term of stability, selectivity and detection limit (Oprea et al., 2018). Amarnath et al. introduced the hybridization of reduced graphene oxide (rGO) with indium oxide (In_2O_3) and nickel oxide (NiO) nanoparticles using hydrazine hydrate as the reducing agent. The morphological and physiochemical properties of the hybrid metal oxide showed unique properties in the gas sensing mechanism and validated its integration for sensitive and selective CO_2 sensing. Fig. 3a shows the CO_2 gas sensing mechanism using rGO layers, which were deposited with p-n junction of NiO and In_2O_3, respectively. The electrode response towards CO_2 gas and ambient air is demonstrated through the barrier thickness, which reflects the p-n junction formed by In_2O_3 and NiO on rGO surface. The system revealed a rapid CO_2 detection with 6- and 5-*sec* response and recovery time, respectively for CO_2 detection in the range of 5–70 ppm (Fig. 3b). The method of integrating carbon nanostructures and metal oxides are encouraged in gas sensing in aim of detecting CO_2 in medical and environmental domains (Amarnath and Gurunathan, 2021). In a recent study, CuO/NiO nanocomposite matrix was developed for detecting CO_2 gas. Apart from the basic properties of metal oxides, the work paved way for the development of charge accumulation layer on sensor matrix (Fig. 3c), which specifically recognizes the gas molecules by manipulating oriented defects on the matrix and other conditions such as moisture, temperature, and humidity. Fig. 3d shows the schematic representation of defect reinforced p-type CuO when adsorbed with CO_2 gas. Chemisorbed oxygen sites promote the sensitivity towards CO_2 by means of coordinated adsorption bond, as shown in Fig. 3e. The results emphasized the in-depth detailing on the metal oxide integration on sensor matrix and the advancement of applying charge accumulation layer with oriented defect states for chemisorbed CO_2 sensing (Vijayakumari et al., 2021).

3.4. Polymer-based sensors

In the line-up of various suitable sensing materials, polymers and their composite have attracted the sensor technology, especially in developing microelectronic chips and devices. Conductive polymers have earned much attention in the growing demand of ideal chemical and biological sensors (Waghuley et al., 2008). Polymer based CO_2 sensors are light-weight, and gives good compactness with chemical and electronic material, which allows it to be used as portable or wearable CO_2 sensors for health monitoring and environmental gas detection (Molina et al., 2020). Polymers as sensing materials play the intermediate role between CO_2 gas and the sensor electrode. Polymers are modelled as it able to capture the CO_2 concentration and converts its analyte property to another physical signals such as resistance, absorption, waves, and other audible variables. The sensitivity with polymers relies on the doping levels, depending on the physiochemical properties of sample and electrode material (Farea et al., 2021; Siefker et al., 2021). Kazanskiy et al. and team developed a unique sensing gold plate with cylindrical *meta*-atoms, which was coated with polyhexamethylene biguanide (PHMB) poly-

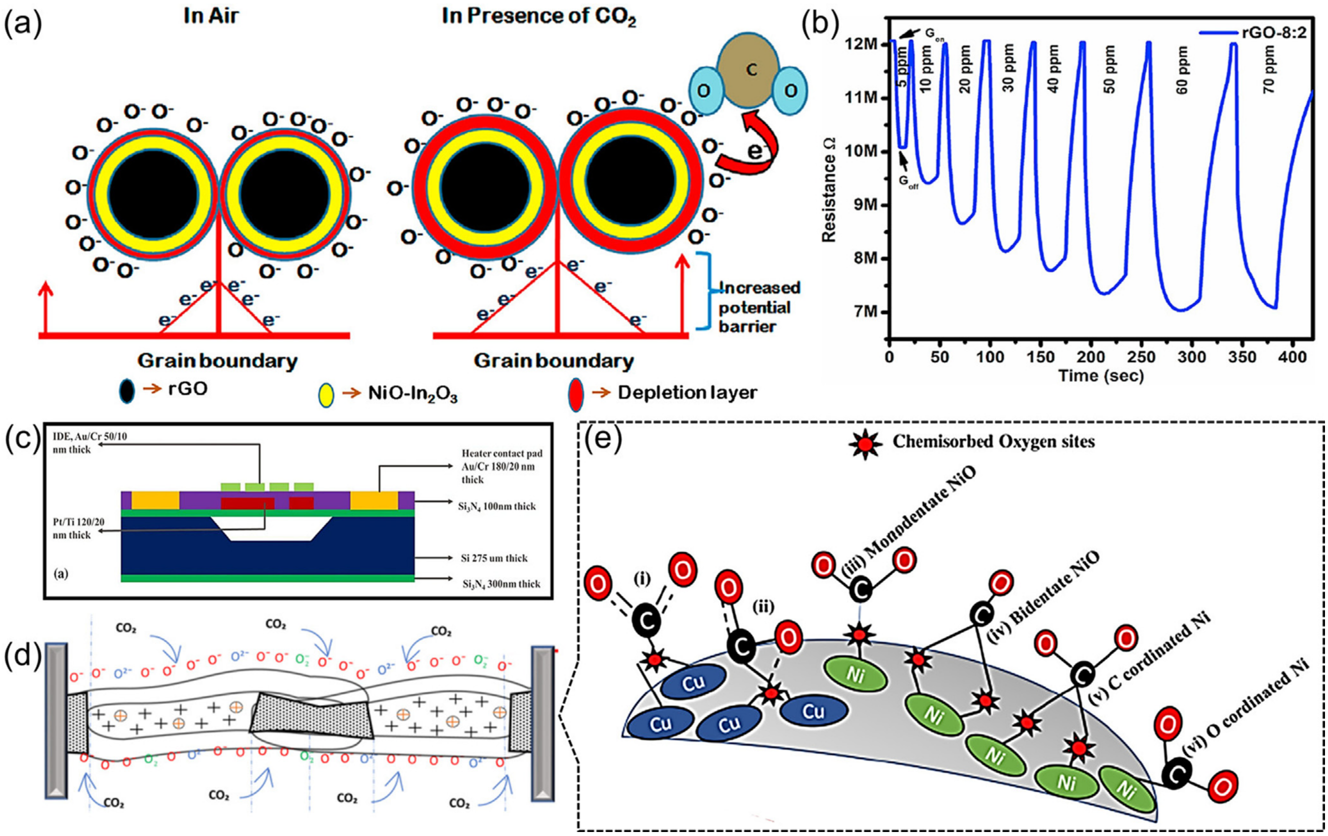

Fig. 3 Metal oxide-based gas sensing mechanisms. (a) CO_2 gas sensing mechanism using rGO layers with p-n junction of In_2O_3 and NiO (b) Sensitivity of rGO-based CO_2 gas sensing, measured with 5 – 70 ppm of input CO_2 gas. Reproduced with permission (Amarnath and Gurunathan, 2021) Copyright 2021 Elsevier. (c) Illustration of CuxO/NiO nanostructured matrix-based sensor for CO_2 detection (d) Schematic view of defect reinforced p-type CuO upon CO_2 gas sensing. (e) Enlarged illustration CO_2 interaction between chemisorbed oxygen sites in a coordinated adsorption bond. Reproduced with permission (Vijayakumari et al., 2021) Copyright 2021 Elsevier.

mer for detecting CO_2 gas. Fig. 4a shows the illustration of gold metasurface sensing plate coated with PHMB polymer. The CO_2 absorption on PHMB reduces its refractive index and shifts the spectrum to blue light. The prominent blue shift is shown in Fig. 4b with the highest CO_2 gas absorbed. The developed system attained maximum sensitivity at 17.3 pm/ppm and showed good potential in detecting CO_2 gas in the range of 0–524 ppm. Fig. 4c shows the determination coefficient at 0.8792, reveal the good interaction between gold metasurface and PHMB polymer (Kazanskiy et al., 2021).

4. Infrared technology for carbon dioxide detection

A primitive breakthrough for a significant sensing mechanism is attained with Infrared (IR) radiation. (Karim and Andersson, 2013). In the late 20th century, IR detectors had their kickoff with the wide range of smart technologies aroused, along with the challenging demand in teletechnologies. The advancement emerged in silicon technology has paved a broad way of IR sensors development, integrated with smart telecommunication technologies. The IR sensor breakthrough was extensive with the competing technology of photon sensors, Schottky diodes, quantum dots, etc. As the severity of human pulmonary diseases were targeted based on CO_2 concentration, IR detectors are applied in medical applications, such as in incubation, neurosurgery, breath analyzer, biomarker detection etc. The uniqueness of IR gas sensors in attaining its specific absorption properties discriminates its advance performance for excellent sensitivity, selectivity, repeatability, resolution, and hysteresis for determining the CO_2 gas (Corsi, 2012; Popa and Udrea, 2019). Among the several classes of IR CO_2 sensors, non-dispersive IR (NDIR) technology and tunable diode laser (TDL) are the most fitting and prominent sensing mechanism applied in detecting and monitoring exhaled CO_2 gas (Vafaei et al., 2020).

4.1. Non-dispersive infrared technology

As stated in the name of the sensor, non-dispersive infrared red (NDIR) sensor does not require the optical dispersive element in the sensing mechanism. It is more straightforward than the disperse IR sensors, where the additional mechanism to slender the light beam for absorption is eliminated. NDIR detecting system provides a promising platform in sensing CO_2 gas, as IR light demonstrate strong absorption band at 4.2 µm. NDIR gas sensor composed of a simplest gas sensing technique, where IR radiation effortlessly interact and absorb with gas particles in a gas chamber and then, the transmittance in IR spectrum is examined to detect the gas concentration (Popa and Udrea, 2019). NDIR technology comprised of broadband IR light source of intensity, I_0, which interacts with the gas sample and results transmitted light intensity, I. It

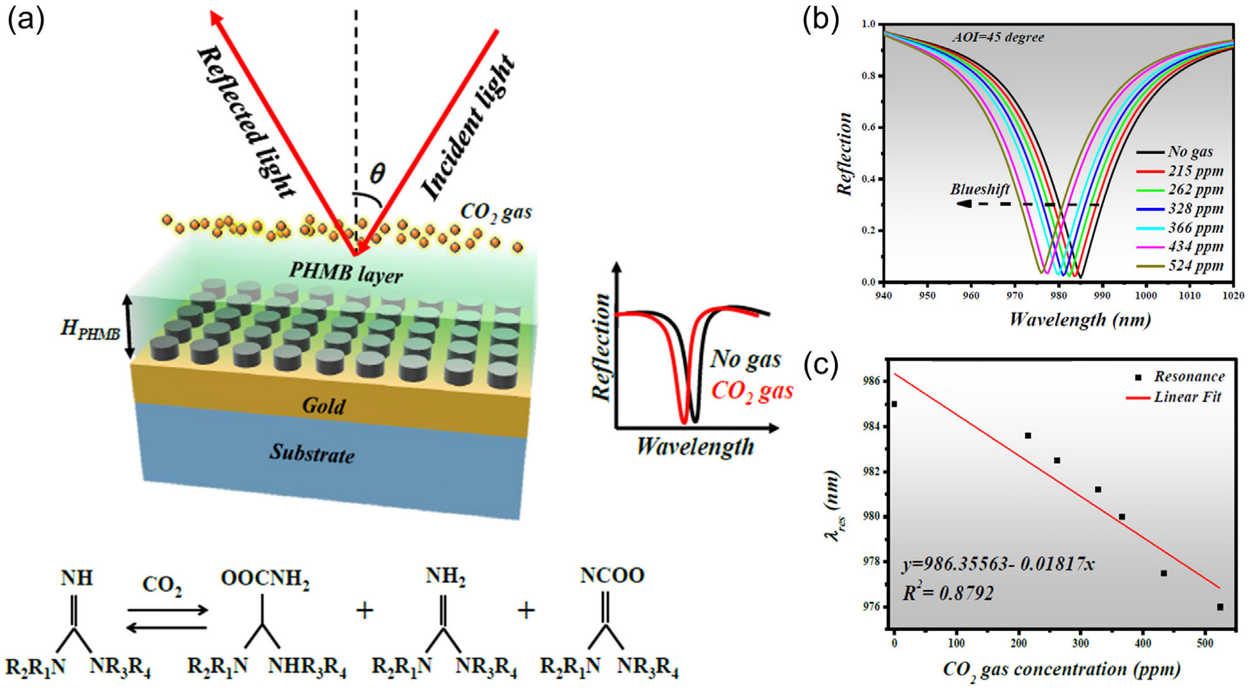

Fig. 4 Polymer based gas sensing mechanisms. (a) Illustration of PHMB polymer coated on gold sensing surface with the reaction occurring between CO_2 gas and amide based functional groups. (b) Sensor response at variant CO_2 gas concentrations. (c) Calibration fitting plot showing the determination coefficient of developed polymer-based gas sensor at 0.8792. Reproduced with permission (Kazanskiy et al., 2021) Copyright 2021 PMC.

demands a periodic single channel calibration or dual cell pathlength to continually assess I_0 for achieving Beer-Lambert absorbance (A) as shown below,

$$A = -\log(I/I_0) \tag{1}$$

Although the finest strategies of NDIR gas sensor have been reported, the research in upgrading the mechanism and eliminating existing drawbacks could not be denied. A notable challenge with NDIR system is the broad light source output and incapability of delivering individual CO_2 features. Besides, NDIR gas sensors often receive objections due to their bulk set-up, which originates from the system installations. The performance of NDIR gas sensor is questioned with the interference exist in the gas sensing system (Jha, 2021). The overlapping of two different gas matrix or water vapor generates interference and disrupts the accuracy of gas detection. As the significant absorption of water vapor takes place from 2 to 8 μm, the corrective factors to eliminate/filter water vapor takes place ahead of the NDIR gas sensing. Some of the corrective actions are the usage of channel-to-channel interference constants coupled with a multi-optical filter. The IR detectors are coupled with bandpass filter of interference gases and the targeted channel is analyzed (Dinh et al., 2016).

As per the developed Si industry, Jia et al. developed a miniaturized NDIR CO_2 sensor on a silicon chip. The set-up of the NDIR sensor is illustrated as shown in Fig. 5a. When the sampling gas is purged into the chamber, the signal at the active filter experience exponential delay with the CO_2 absorption, whereas the reference filter will remain unchanged. Hence, the CO_2 gas was determined by comparing the signals in both channels. The 3D and 2D illustration of the NDIR sensor is shown in Fig. 5bi and 5bii, respectively. The gold-coated cavities confine the light into the chambers and couple the signals to detector. Fig. 5c shows the normalized absorbance measured for the CO_2 sensor, showing a limit of detection of 100 ppm (inserted figure). In addition, the NDIR CO_2 sensor was able to response in ~ 2.8 s, with the developed small footprint as shown in Fig. 5d (Jia et al., 2019). Thereafter, the team developed a silicon substrate based NDIR CO_2 sensor using a mid-IR light emitting diode (LED) optical source, two mid-IR photodiodes as detectors and an integrating cylinder with access waveguides (Fig. 6a). The emission spectrum of the LED, and photodiodes were examined to specify the spectral response of sensing diodes and the CO_2 absorption band. Fig. 6b indicates that sensing diode overlaps with CO_2 absorption band, whereas reference diode shows no overlap. With the absorption spectral reference, the developed NDIR CO_2 sensor chip integrated with *trans*-impedance amplifiers on a PCB is shown in Fig. 6c. The sensitivity of detecting CO_2 is evaluated through the sensing signal normalized with reference signal. Fig. 6d presents the CO_2 response, which is quite noisy due to the imbalance of sensing channel applied on the PCB and justified that no water interferences were detected in the system. A 750 ppm of lowest CO_2 concentration was able to be detected using the NDIR CO_2 sensing system. The work emphasized the development of miniaturized NDIR CO_2 sensing platform as a potential low cost detecting strategy (Jia et al., 2021).

4.2. Tunable diode laser technology

Tunable diode laser (TDL) technology is a state-of-the-art infrared system, where the conventional absorption spectral is combined with advanced TDLs. Unlike NDIR technology,

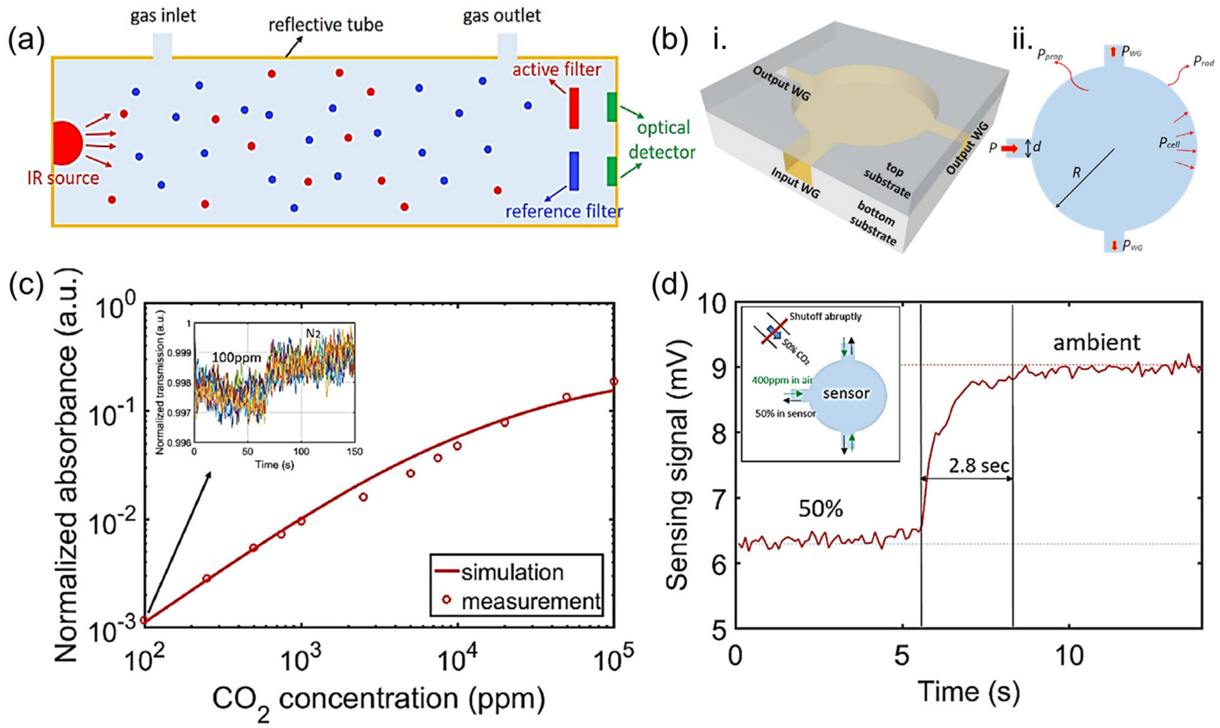

Fig. 5 NDIR CO$_2$ gas sensing technologies. (a) Simple NDIR gas sensor schematic diagram showing the IR source, reflecting gas ways, optical filters, and optical detectors. (b) i. 3D and ii. 2D visualized mage of NDIR sensor developed using gold coated hollow cylindrical cavity. (c) Absorbance reading against CO$_2$ gas concentration, inserted Fig. shows 100 ppm of detection limit. (d) Sensing signal against response time chart showing that the developed sensor responses in ~ 2.8 s. Reproduced with permission from (Jia et al., 2019) Copyright 2019 PMC.

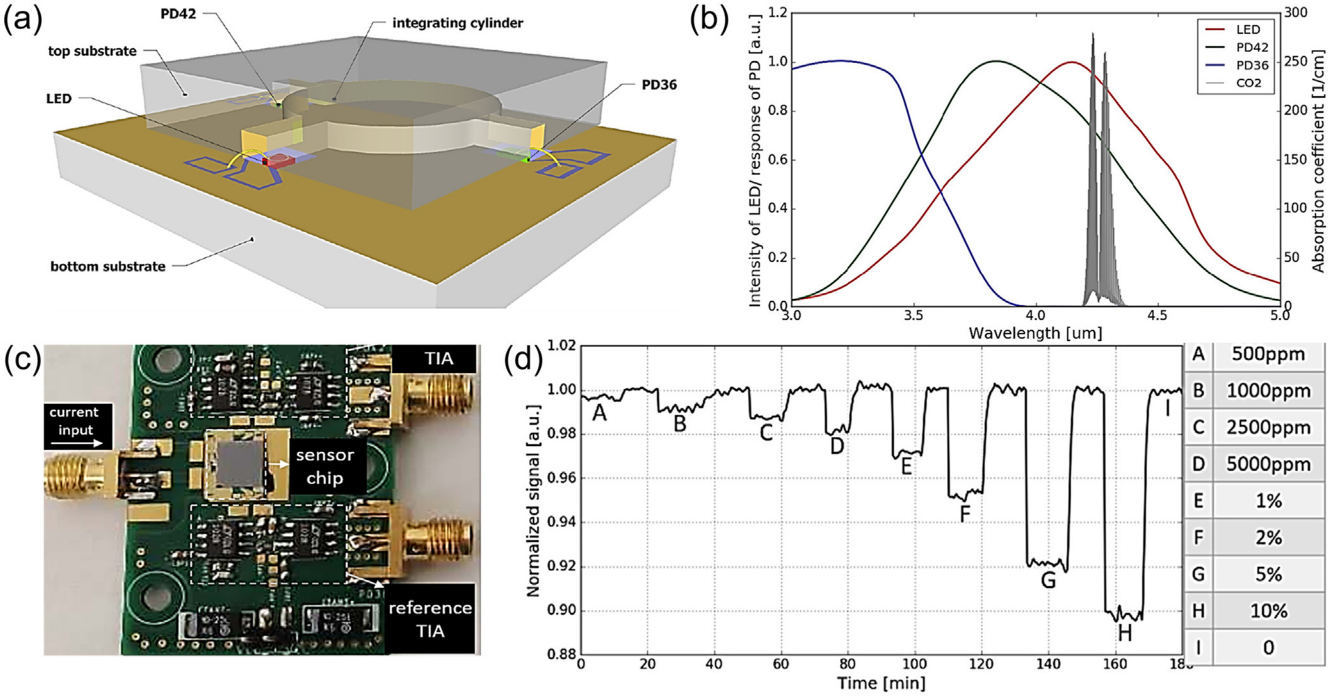

Fig. 6 NDIR CO$_2$ gas sensing technologies. (a) Schematic illustration NDIR CO$_2$ gas sensor developed using LED and photodiodes with an integrating cylinder. (b) Absorption spectral response of sensing and reference diodes in the developed system. (c) Digital image of PCB integrated with NDIR sensor and *trans*-impedance amplifiers. (d) Signal responses against time at various CO$_2$ gas concentrations, indicating the sensitivity of developed system. Reproduced with permission from (Jia et al., 2021) Copyright 2021 PMC.

TDL technology gives narrow spectral resolution to discern individual CO_2 rovibrational features. This eliminates the need for calibration and enables the continuous measurement of light source intensity and transmitted light intensity (I/I_0). In a TDL system, the laser spectrum is repetitively scanned through the central frequency (v) of gas absorption line and the detector records the transmitted laser intensity (Pleil and Christensen, 2021). According to the Beer-Lambert law, the relation of incident laser intensity (I_0) and transmitted intensity (I) is expressed as shown in equation below.

$$I(v) = I_0(v)e^{-\alpha(v)L} \tag{2}$$

The α(v) represents the absorption coefficient at central frequency and the L stands for the optical path length (Henderson et al., 2018). Single mode laser operation is the primary technology introduced for CO_2 detection due to its broad tuning range. The single mode laser results in a minimum A highly sensitive system with least signal-to-noise ratio and low detection limit CO_2 measurement is attained by utilizing the multi-pass cells, which concurrently enhances the system path length and modulation methods (Kireev et al., 2018). CO_2 gas shows comparatively good absorption intensity in mid-infrared wavelength region than in near infrared. The modulation of TDLs enables wavelength tuning in a narrow spectrum range by manipulating the input temperature and current of the system. Utilizing multi-pass gas cells and TDLs with wavelength/frequency modulation system draws a very low detection limit in gas sensing. The multi-pass nature of the optical absorption spectrum enhances the sensitivity as it is coupled with high resolution laser sources (Cui et al., 2020).

TDL absorption spectroscopy has upgraded in the current state of breath analysis, especially in CO_2 sensing. Application of external cavity quantum cascade laser (ECQCL) in mid-infrared region was presented as advancement of TDL for real-time breath analysis. A study aimed to detect CO_2 and CO in healthy non-smokers and smokers through the TDL spectroscopy. Fig. 7a shows the measurement set-up of ECQCL, which surrounds the breath sampling unit and the TDL spectroscopy integrated with multi-pass cell and wavelength modulation. The real-time exhaled CO_2 was measured, and the reading is comparatively analyzed with conventional capnography. The system showed a low detection limit at 650 ppm with 0.14 s spectral acquisition time. The exhaled pattern for measured CO_2 and CO for one breath cycle is shown in Fig. 7b. The variation in rise and decline of exhaled CO_2 pattern with TDL and capnography measurement may be caused by the different measurement locations and targets. Nevertheless, the study showed 8.5×10^{-8} cm^{-1} $Hz^{-1/2}$ sensitivity in real-time CO_2 measurement and validated the system and the performance as an advanced and enhanced system for breath analysis (Ghorbani and Schmidt, 2017). Recently, Christensen et al. (2022) developed In-Mask Carbon Dioxide and Water Vapor Sensor (IMCWS) to measure CO_2 and water vapor during jet fighter flight, as the TDL sensor was integrated in the pilot mask. Fig. 8a shows the schematic view of the IMCWS, whereas Fig. 8b shows the system schematic of the developed set-up. TIMCWS measures CO_2, water vapor, pressure, and temperature at 100 Hz by capturing the breathing profiles and flow dynamics of a pilot during flight. The direct placement of TDL sensor (Fig. 8c) in pilot mask acquires rapid breathing data with good time response. Fig. 8d shows the breathing cycles of a pilot recorded during flight, representing the separated mechanical flow of CO_2, vapor, and pressure in each breath cycle. The innovation was developed due to the cases reported on pilot stress and fatigue incidents during flight caused by subtle external factors. High-performance aircraft life support system is in demand for providing comfort breathing and monitoring its mechanical flow during variant flight level (Christensen et al., 2022). TDL spectroscopy eliminates the calibration step for real-time gas sensing, which is highly implemented in exhaled breath biomarkers analysis, with tidal concentration lower than ppb range, yet results in good absorbing transitions. Hence, TDL absorption spectroscopy is well suited for multiple gas sensing system, which plays a significant role in clinical practices of exhaled breath analysis. Table 1 summarizes the recent works reported for detecting CO_2 from exhaled breath with IR technology and its comparison with other existing technology. Based on the

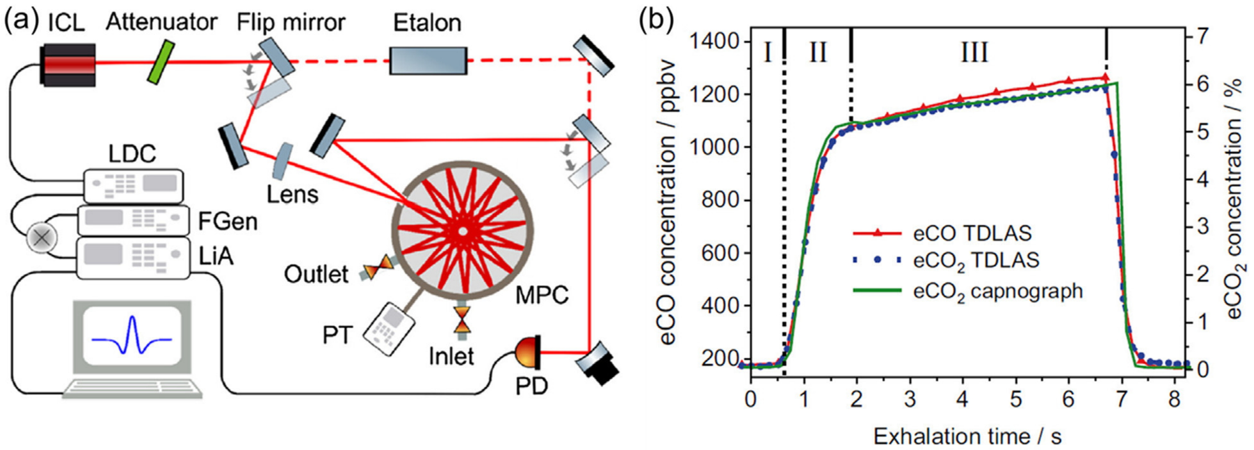

Fig. 7 Advancement of IR spectroscopy with TDLs. (a) Experimental set-up of TDL absorption spectroscopy using ECQCL and Herriot multi-pass cell, equipped with breath sampling unit for exhaled breath analysis. (b) Exhalation profile of CO_2 obtained by TDL spectroscopy in comparison to capnography, which validates the good sensitivity and selectivity of ECQCL based TDL spectroscopy for exhaled breath analysis. Reproduced with permission (Ghorbani and Schmidt, 2017) Copyright 2017 Springer.

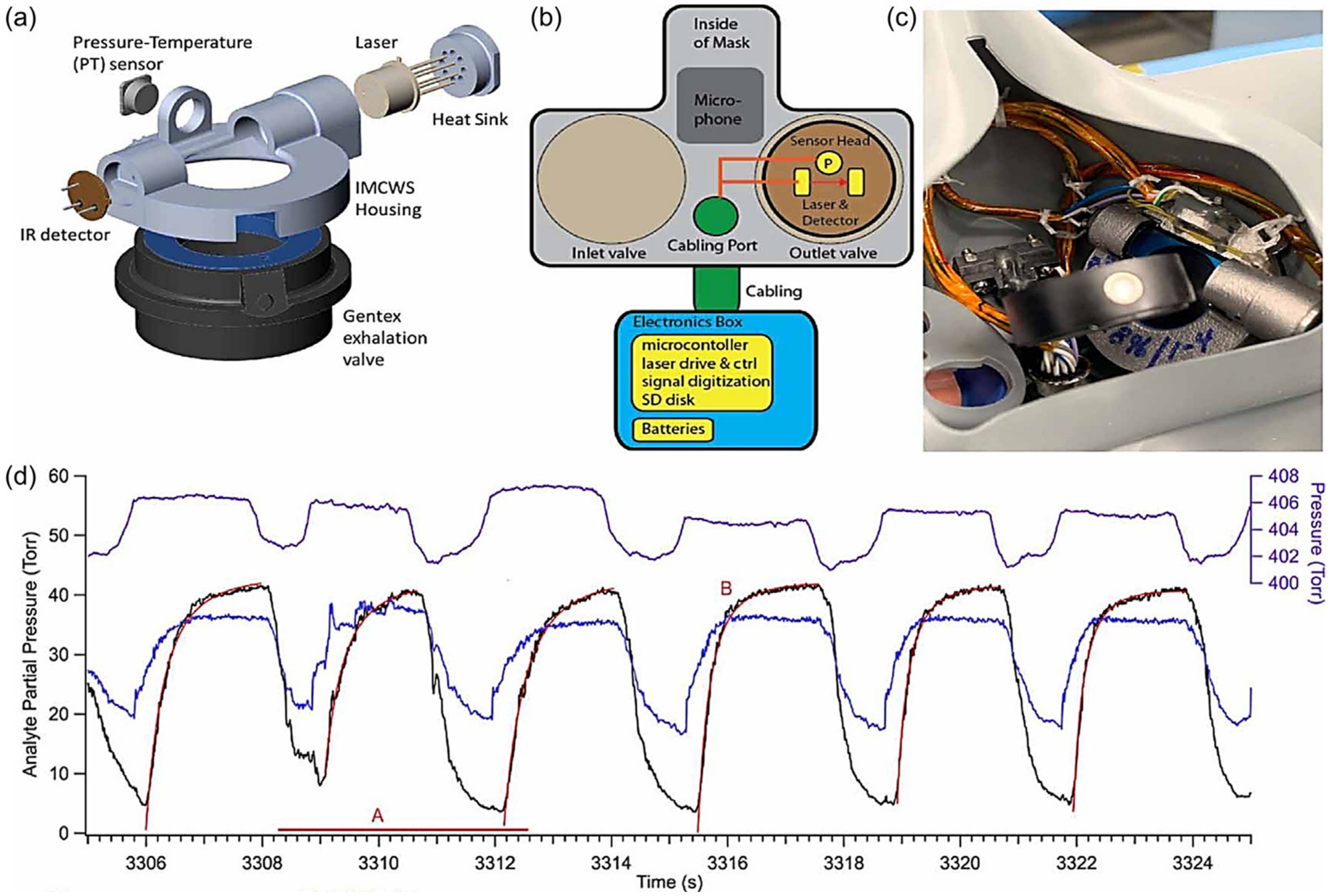

Fig. 8 (a) Design of TDL based In-Mask Carbon Dioxide and Water Vapor Sensor (IMCWS) for detecting CO_2 along with water vapor, pressure, and temperature for fighter pilot. (b) Schematic view of the developed system. (c) Digital image of IMCWS breathing mask. (d) Mechanical flow of CO_2, vapor, and pressure in each breath cycle of a pilot recorded during flight. Reproduced with permission (Christensen et al., 2022) Copyright 2022 IOP Publishing.

table, it is notable that the variety of CO_2 gas sensors are well established with low detection limit. Nevertheless, the innovation of targeting CO_2 from exhaled human breath is limited, compared to the environmental and industrial gas detection. The specifications stated in the table are expected to expand the development of CO_2 gas sensor, precisely for exhaled human breath analysis.

5. Infrared sensors in Internet of Things (IoT)

IoT is one of the emerging technologies in the state of art of global networking. IoT is well-received all over the world, giving a barrier-free communication system throughout the globe. In the current decade, IoT is on track with the growth of science, technology, and economy for a superior and rapid world revolution (Aghdam et al., 2021; Ketu and Mishra, 2021). A networking system facilitates the functional tasks between the small devices. The data generated within a network is presented through a telecommunication system. The small things utilized in IoT are commonly recognized as smart things, serving as the intermediator within complex networking using internet resources. IoT is then extended to intelligent services through deep learning and machine learning, resulting in the advancement of artificial intelligence (AI) (Lutta et al., 2021; Ul Alam and Rahmani, 2020). A statistical report on IoT revealed that IoT will be able to connect over 500 billion devices within the internet settings by the end of 2030. Such advancement is expected to have a high revenue turnover in the IoT business as the IoT revolution has been surpassed by human in their daily lifestyles (Mahendran et al., 2021).

Sensors are classified as one of the preliminary hardware equipped in IoT networking, which are designed as the critical trade-off between sensing mechanism and wireless networking. The advantages of IR light wavelength and its absorption properties have significant input to electronic devices for an accurate and fast sensing mechanism, which are effortlessly incorporated to the IoT wireless networking. The IR sensor installed on smart devices generates an incredible set of data and transmits to a controller system, where it is transmitted to process or determine an action sequence (Jain et al., 2021). Although the significance of IR sensor has been intensively recognized in IoT networking, it has not yet become pervasive to humans for home use for medical health monitoring. In general, gas sensors encounter sensors drifting, which may be caused by the aging of sensor or environmental influences (Ye et al., 2021). Sensor drifts are traditionally resolved by troubleshooting the hardware of gas sensing system. However, it adds the cost of development and results in unstable and

Table 1 Existing techniques versus Infrared technology for detecting CO_2 from exhaled breath.

Electrochemical platforms

Electrocatalyst	Electrolyte	Operating temperature	Response time	Detection limit	References
Lithium garnet	Li7La3Zr2O12 solid electrolytes	Room temperature	1 min	400–4000 ppm	(Struzik et al., 2018)
Li (II) carbonate electrode	Lithium (III) phosphate solid electrolyte	Room temperature	1 min, 59 mW power	500–10,000 ppm 50.5 mV/decade Nernstian slope value	(Lee et al., 2017)
Iridium metal wire	Lithium bicarbonate/Potassium nitrate	870 °C	4 – 5 min	10^{-4} to 10^{-2} M	(Yao and Wang, 2002)

Sol-gel system

Catalyst	Type of sol–gel	Operating temperature	Response time	Detection limit	Reference
Fluoride ion (Quenching effect)	Hydrazinecarboxylate derived naphthalene	130 °C reaction temperature, Sensing at room temperature	Nil	Nil, Qualitative detection through fluorescent color change	(Liu et al., 2017)
Tetraethyl orthosilicate (TEOS) with coreless fiber	Silica matrix	50 °C	Nil	0.034 dB (log scale)	(Lalam et al., 2020)
Hydroxypyrenetrisulfonic acid (HPTS)	Silica (Polydimethylsiloxane, (3-Aminopropyl) triethoxysilane, TEOS)	Room temperature	13.49 ± 2.4 s with 12 months recovery time	6.69 ± 0.9 mM,	(Nivens et al., 2002)
Titanium particles (0.5 – 1.5 µm)	Silica-doped matrix with the 1-hydroxypyrene-3,6,8-trisulfonate (HPTS) fluorescent indicator	387 ppm	Nil	80 ppm, a quantitation limit of 200 ppm	(Dansby-Sparks et al., 2010)
Sol-gel Aluminum oxide	Hybrid chitosan/calcium aluminosilicate	25 – 100 °C	Nil	100 ppm	(Abou Hammad et al., 2019)

Metal oxide-based sensors

Sensitive material	Strategy	Operating temperature	Response time	Detection limit	Reference
Copper oxide/nickel oxide nanomatrix (Cu_xO/NiO)	Charge accumulation layers	250 °C	Nil	125 ppm	(Vijayakumari et al., 2021)
Nickel oxide and indium oxide nanoparticles (NiO-In_2O_3)	Resistance of reduced graphene oxide sensing electrode	Room temperature	6 s	5 ppm	(Amarnath and Gurunathan, 2021)

Polymer-based sensors

Polymer	Strategy	Operating temperature	Response time	Detection limit	Reference
Polypyrrole with Ferum (II) chloride catalyst	Resistance and voltage drop measurement of system	Room temperature	210–270 s	100 ppm	(Waghuley et al., 2008)
Polyether sulfone	Wavelength examination of fiber Bragg grating sensor	50–250 °C	3.27 min	0.78 % (0.77 pm/%)	(Z. Zhou et al., 2021)
Poly(ethylene oxide) and poly(ethyleneimine)	Frequency shift response of mass sensor	Room temperature	30 min	0.12 Hz ppm^{-1}	(Siefker et al., 2021)

Infrared technology

Laser spectroscopic technique	Specification	λ (µm)	Optical path length	Response time	Detection limit/Measured concentrations	References
NDIR	Hollow metallic cylindrical cavity with 4 mm diameter giving optical path length of 3.5 cm	4.25 µm	3.5 cm	2.8 s	100 ppm	(Jia et al., 2019)
NDIR	light emitting diode (LED) and photodiode (PD) light used as source/detector	4.25 µm	20 mm 70 mm	4 s 30 s	0 – 2000 ppm range	(Gibson and MacGregor, 2013)
NDIR	Miniature cylinder 20 mm diameter × 16.5 mm height	Absorption band at 4.2 µm Non-absorbing reference band at 3.95 µm	3.2 cm	23 s	1 ppm (noise equivalent absorbance 3×10^{-5} AU)	(Hodgkinson et al., 2013)

(continued on next page)

Table 1 (*continued*)

Electrochemical platforms

Electrocatalyst	Electrolyte	Operating temperature	Response time	Detection limit		References
TDL	Vertical-cavity surface-emitting laser (VCSEL) and a multi-pass cell	1.58 µm	20 *m*	168 s	100 ppm (0.769 %)	(Lou et al., 2019)
TDL	External-cavity quantum cascade laser (EC-QCL), a low-volume multi-pass cell and wavelength modulation spectroscopy	4.50–4.96 µm (CO and CO_2 detection range)	3.99 *m*	0.14 s	650 ± 7 ppmv (Noise equivalent sensitivity: 8.5 × 10–8 cm^{-1} $Hz^{-1/2}$)	(Ghorbani and Schmidt, 2017)

unreliable technology for long-term use. IoT has broadened the room for resolving the sensor drifting through software technology. The advancement in univariate IoT technology has reduced the cost of debugging sensor drift and eased the implementation in accordance with the sensor application. The algorithmic approach is one of the most applicable choices of method to overcome sensor drifting. The necessary conditions and precautions for sensor drifting compensation is precisely delivered in the algorithm, which is perfectly integrated with hardware of gas sensing system through the IoT technology (Dong et al., 2021; Zhu et al., 2021). As a part of artificial intelligence (AI) advancements, machine learning models plays significant role in developing the algorithms, which effortlessly removes the erroneous data and solves the complexity of subsystem, without disrupting the programmed purpose of the smart tool. As the real-time gas sensing systems are prone to erroneous data due to the sensor drift, temperature fluctuations and long operating hours, IoT integrated machine learning models are a popular choice of method practiced for developing algorithms and program a smart gas sensing mechanism (Sahu et al., 2021).

6. Infrared-IoT technology in carbon dioxide sensors for respiratory monitoring

Internet of Things (IoT) in medical and healthcare applications took some time in comparison to electronic industries, yet it has exponentially grown for its excellence. IoT excelled in medical health due to the massive capability of IoT in controlling and monitoring illnesses continuously and previously diagnosed history (Aceto et al., 2020; Muhsen et al., 2021). Due to modern civilization, the aged group people and the adolescents tend to stay alone in their homes, while the caretakers are engaged with daily working routines. Such situations often result in the last stage diagnosis of any illness, due to the delay in monitoring one's health condition. Hence, an efficient method of healthcare monitoring at home environment is required, which can monitor and hold the record of health condition in any range of specifications (Ketu and Mishra, 2021; Mahendran et al., 2021; Surantha et al., 2021). Although several home monitoring healthcare devices exist, humankind has very low belief in such devices, in fact has high level of trust towards doctors and hospitals. Therefore, there is need to develop a medical device which creates faith in people for their safe medical condition and able to provide relevant remedies as per advised by doctors. The emergence of IoT technology shows high potentiality in the information technology domain among many small medical devices to enable smart medical healthcare system with the remote and clous server. Remote health record monitoring provides the facility of recording the health parameters anywhere and anytime, which is stored in the global cloud server for further follow-ups. The system eliminates physical recording techniques and maintains the data integrity for further accessibilities (Aghdam et al., 2021; Lutta et al., 2021).

Asthma, COPD, pulmonary hypertension, lower respiratory tract infection, and occupational lung diseases are several respiratory disorders causing a high number of deaths. At such condition, IoT augmentation in medical healthcare, especially in respiratory illness monitoring is a great approach for medical personnel and patients for self-care applications and prevent or treat respiratory disorders at early conditions (Ramírez López et al., 2019; Tsai et al., 2021). Real-time asthma monitoring devices are developed to record the respiratory conditions and detect the abnormalities at early stage of asthma. IoT based asthma monitoring methods are introduced. A study conducted by Raji, and the team showed a prospective respiratory monitoring system using an IR temperature sensor to measure the respiratory rate. An alarm system is equipped into the system to trigger the patient by sending a message if the threshold level was reached. With the IoT web server system, doctors and facilities receive the respiratory information instantly for record and consultations (Raji et al., 2017). In another study, IoT technology has proposed real-time asthma monitoring and provides appropriate medication for the diagnosed condition. The developed smart tool can identify external conditions, which are not safe for patients and send messages to migrate to a better environment. The IoT technology is composed of cloud computing, machine learning and big data analysis methods. The proposed model is acceptable for future development, where it is convenient to modify the features of the tool as demanded in future works (G. AL-Jaf and H. Al-Hemiary, 2017). A recent study has developed a non-invasive detection strategy using nanomaterial hybrid IR sensor to identify volatile organic compounds from exhaled breath samples. Gold nanomaterial based electronic system were integrated with a data collecting server system, which enables user to obtain the results from the smartphone. The system aimed to reduce crowd at hospital facilities due to the risk associated with the environment and alternatively maintain the records of infected patients (Shan et al., 2020). The recent reviews presented show the implementation of IR sensing strategies with IoT technology (Umeda et al., 2021; Zhou et al., 2020). However, the innovation of non-invasive exhaled CO_2 gas monitoring and its integration with the IoT technology is yet to be established. The predominant gas monitoring tools are mainly focused during anesthesia, where the concentration of CO_2 in exhaled breath during anesthesia helps to detect unexpected changes in respiration when a patient is sedated (Galetin et al., 2021). The concentration of CO_2 is observed but not recorded or saved for future analysis. Although medical personnel showing good agreement in the specificity of CO_2 monitoring for detecting respiratory conditions, there are limited innovations reported for utilizing IR based CO_2 sensor and correlating it with IoT technology for periodical and real time respiratory diagnosis and monitoring. Like pressure checker, a portable, and real-time respiratory monitoring tool is expected to be available in the market for humans to carry out self-test at home and consult medical personnel with recorded data.

7. Clinical challenges in carbon dioxide gas sensing

The fascinating benefits of IR spectroscopy has been proven through the highlighted reports, which emphasized the promising platform for IR sensors in multiplexed applications. The advancement has been well-established in medical healthcare, mainly in diagnosing respiratory disorders. IR spectroscopy in tracing the variety level of gaseous states implemented in breath analyzers. It has widened the room for improvement in deployable breath analyzers for respiratory monitoring at clinical settings. In specific, IR CO_2 gas sensors are inherited from environmental gas detection, towards medical application in detecting human respiratory condition based on the level of CO_2 in breath. As discussed in the review, NDIR and TDL CO_2 gas sensors have shown high potential and an exponential growth in the breath analysis application. However, several limitations hold back IR CO_2 gas sensors from their vast application in medical healthcare tools. The specificity of sensor in molecular selectivity from the exhaled breath, at its regime frequency range requires further polishing in developing the high sensitivity and specificity sensing platforms. The IR light absorption properties excel the detection of CO_2 gas from breath sample, yet it's rare for a lower detection limit (ppt/ppb) achievement at clinical practices. Besides, the challenges in miniaturization of IR CO_2 gas sensing set up and its integration for field use have impacted the application of IR gas sensors in clinical breath diagnostics. In addition, the miniaturization comes along with high power consumption and cost due to the expenses involved in IR light sources. The impacts of water vapor with the strong absorption in IR spectrum have been minimized by selecting appropriate light sources in the spectral window and using suitable filtering units. Apart from that, a variety of strategies have been introduced to counterpart this issue, yet the ideal solution is yet to be recognized. IR CO_2 gas sensors may be a vital element in the future of monitoring respiratory illness through the exhaled breath at clinical space. There are several hiccups identified, yet the advancement notified in the semiconductor electronic industry has shown a significant breakthrough towards the IR gas technologies. The innovations in quantum computing introduced peculiar phenomena including quantum tunneling, quantum entanglement, and the ability of quantum particles to simultaneously exist in more than one state at its subatomic level. The advent of quantum computing has tremendous significant in generating compact IR sensing systems, with multiplexed utilities. Transduction strategy has equal importance towards developing a high-performance IR gas sensor, as it is expected to be excellent in quantitative interaction between photons and molecular constituents. Semiconductor waveguides have shown a significant step forward towards the efficient and reproducible sensing devices with the propagation of IR radiation. Personal respiratory monitoring devices are expected to be handheld, that pave the way for direct in situ monitoring, where IR component is the significant component in the simplification of device, complementary to the sensor performance. IoT in medical health has developed but it has not matured, due to the existing drawbacks that are yet to be resolved. IoT is highly expected to contribute for monitoring respiratory illness, as it is closely related to several severe diseases such as asthma, pulmonary odema, COPD, and the most affected pandemic, SARS-CoV-2 diseases. The primary objective of IoT in medical health monitoring is to control and prevent diseases. IoT technology in medical healthcare is expected to ensure high-quality monitoring systems, identify the suspected patients at early stage of illness and effectively consult and improve the patient condition, with least physical contacts and paper works. The fusion of IR CO_2 gas sensing mechanism with IoT technology aims in the improvement of interoperability of the entire system, which ensures no leakage and enhances the distribution and networking. Hence, there is demand for developing conductive and high-accurate IR CO_2 sensors that instantly communicate with IoT technology for creating an excellent telediagnostic and telemedicine for monitoring respiratory disorders at clinical settings. Fig. 9 resembles the non-invasive respiratory disorders monitoring using exhaled breath, which pass-by a high-performance IR CO_2 gas sensors and analyzed using IoT technology via smart-phones. The modern medical IoT approaches real-time medical healthcare with the concept of 'easy to diagnose, easy to prevent, easy to treat and easy living'. IR CO_2 gas sensors and its integration with IoT has set the platform and urgent improvements are in demand for achieving real-time respiratory illness monitoring.

8. Conclusion and future perspectives

Gas sensors have received huge attention for improvement due to their vital responsibility in determining the gas concentration and flow in several important aspects, such as environmental and manufacturing industries. The efforts in developing high performance CO_2 gas sensors are significant, not only for the environmental greenhouse monitoring but also for monitoring human respiratory illnesses. A variety of gas sensors have been introduced in the literature, and many were focused on sensing toxic CO_2 gas concentration for environmental safety and monitoring. Comprehensive studies on IR based gas sensors were presented, revealing the innovation of IR light absorption properties and its amalgamation in gas detection, mainly for monitoring respiratory disorders from exhaled breath. The NDIR and TDL CO_2 gas sensors are well reported in detecting the gas at multiplexed conditions, yet there were several drawbacks in term of clinical conditions such as,

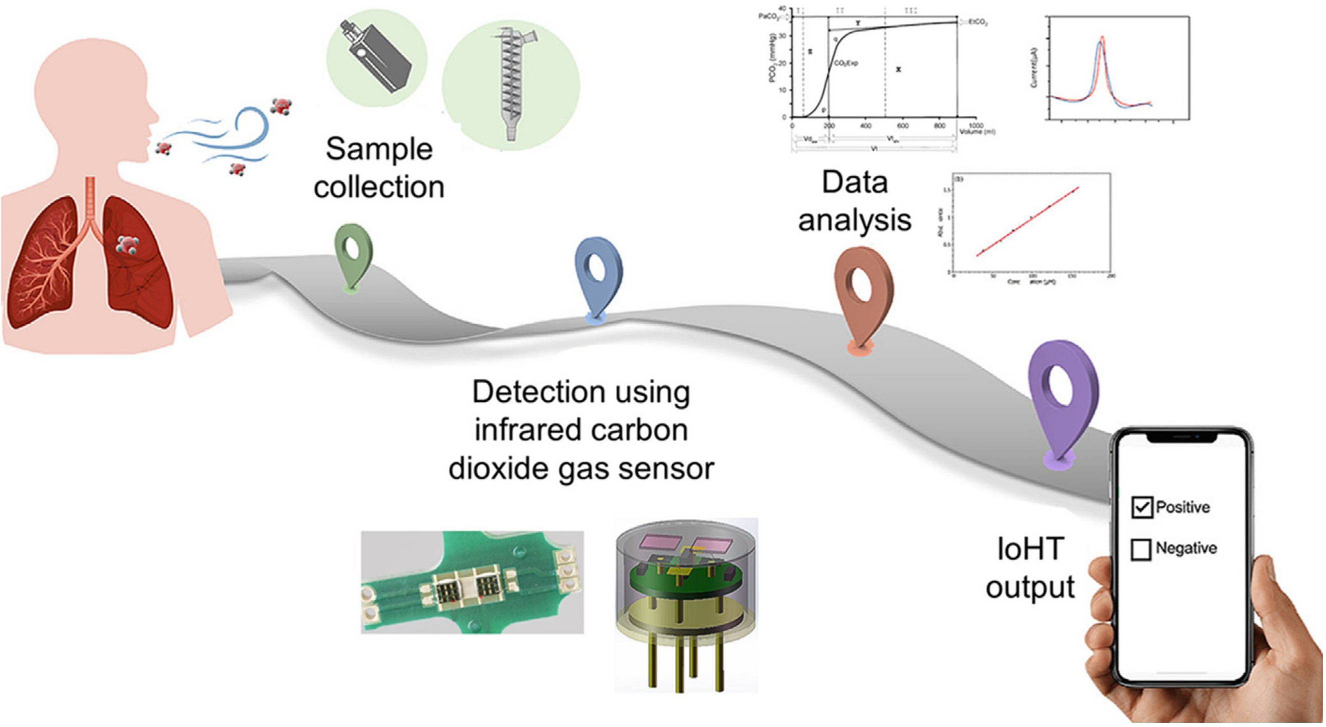

Fig. 9 Architecture of respiratory illness monitoring and diagnosis using ideal IR CO_2 gas sensors using effortlessly collected exhaled breath. The sensing mechanism is expected to provide prompt readouts for data analysis and maintain a secured and optimistic data saving using IoT networking, which is easily accessible at clinical setting and home environment.

detection limits, interferences and IR light sources and detector. However, the efforts encountered with the growing semiconductor and electronics industries have given a step forward approach in generating ideal IR CO_2 gas sensor. In the exponential growth of telediagnostics, IR CO_2 sensors incorporation with IoT technology for real-time monitoring of respiratory illnesses are overviewed. Several unconventional reports presented on the strategies to bring forward IR CO_2 gas sensing mechanism into IoT technology have discussed to emphasize the current domain for diagnosing and treating patients from home and ensure the robust reduction on the number of deaths caused by respiratory illnesses. The challenges and future preference on clinical respiratory disorder detection and its monitoring from home-environment were discussed.

Although the advanced IR CO_2 gas sensors have demonstrated excellent prospects in human breath analysis, the goal of combining IoT technology in clinical monitoring and diagnosis is emerging to relieve the dependence of patients at medical facilities. Due to the lack of research about integrating IR technology and IoT technology, the related sensing properties like detection limit, stability, sensitivity, and response time should be further enhanced to meet the requirements of human breath analysis. In addition, the future of clinical respiratory monitoring system is expected to improve the interoperability of the entire system, which ensures no leakage and improves distribution and networking. As a result, IR CO_2 exhaled breath analysis coupled with IoT technology can be continuously enhanced considering the issues already present, suggesting significant development potential in the enhancement of sensing performances and diagnosis accuracy.

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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