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Review article

State-of-the-art carbon metering: Continuous emission monitoring systems for industrial applications

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ABSTRACT

In response to the urgency of climate change, nations are enforcing stricter regulations on emissions, particularly in the energy sector, intensifying the focus on precise carbon measurement. This review systematically examines carbon emission scenarios by analyzing energy system structures and advancements in monitoring and metering technologies. We introduce the concept of real-time, dynamic carbon metering, which enhances carbon accounting accuracy through context-specific measurements. Emphasizing key technologies for Continuous Emission Monitoring Systems (CEMS) in stationary sources, this paper highlights innovations in sensor technology, such as NDIR and nanotechnology-enabled sensors, that improve detection sensitivity and reliability. Key challenges for CEMS implementation are identified, including high costs and regional variations in emission standards. Through a bibliometric analysis using CiteSpace, we reveal emerging trends in integrated gas monitoring, real-time data analytics, and the role of artificial intelligence in refining data interpretation. Our findings underscore the need for policy-related frameworks that incentivize technological innovation, facilitating the development of cost-effective and adaptable monitoring solutions to support accurate, actionable carbon data for effective emissions management and alignment with global environmental goals.

1. Introduction

People are beginning to pay attention to air pollution and air quality since 1970s. The understanding of volatile organic pollutants (VOCs) as a source of air pollution has gradually increased. Although the emission governance of greenhouse gases (GHGs) is slightly later than that of VOCs, with the increased awareness of climate change and environmental issues, significant progress has been made in the attention and action on GHGs emissions. The Kyoto Protocol and the Doha Amendment specify seven GHGs required to be controlled, including carbon dioxide (CO2), methane (CH4), nitrous oxide (N2O), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), sulfur hexafluoride (SF6), and nitrogen trifluoride (NF3) [1]. Of these gases, carbon dioxide (CO2) has the most significant

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proportion, accounting for approximately 76 %, followed by methane (CH4) at around 16 %, nitrous oxide (N2O) at approximately 6 %, and other gases together accounting for about 2 % [2]. According to the International Energy Agency, global energy-related carbon dioxide (CO_2) emissions account for 73 % of total emissions, of which coal-fired power generation contributes about 40 % of CO_2 emissions. Stationary emissions have the most significant proportion of GHG emissions, accounting for about 70 % [3]. Road and other transportation sectors rely on fossil fuel combustion for energy supply, accounting for approximately 25 % of the total GHG emissions [4]. Among fixed emission sources, continuous emission monitoring system (CEMS) has become the mainstream technology of carbon emission monitoring, with a global penetration rate of more than 70 %. For example, the Neurath coal-fired power plant in Germany achieved a carbon reduction of approximately 15 % through real-time CO_2 monitoring with Internet of Things (IoT) technology combined with high-precision sensors and optimization of the combustion process with machine learning algorithms, statistics that show that accurately quantifying carbon emissions is critical to achieving carbon reduction targets.

Shared Socioeconomic Pathways (SSPs) were employed to classify emissions originating from the energy system. This approach was chosen to encompass a broad spectrum of carbon emission scenarios and enhance the precision of emission assessments. Among them, stationary emissions sources refer to scenarios where factories, enterprises, catering services, boilers, kilns, and households emit GHGs from fixed exhaust pipes. The GHG emissions from the extraction, conversion, and transportation of primary energy sources in the energy system are a minor proportion, only a few percentage points [5]. Accurately quantifying carbon emissions across various industrial sectors is fundamental to achieving carbon reduction targets. However, the commonly used carbon accounting approach faces numerous challenges, as it requires precise recording of carbon activity data at each industrial stage—a task that small enterprises often lack the resources to perform. Furthermore, the accuracy of carbon activity data, which is essential for carbon accounting, is heavily influenced by human factors, introducing significant uncertainties. In contrast, carbon monitoring offers a more objective method by directly quantifying greenhouse gases emitted into the atmosphere using hardware detection devices. Currently, continuous emission monitoring systems (CEMS) used in fixed-source scenarios cover approximately 70 % of carbon emissions within the energy industry. Therefore, the research and development of carbon monitoring technologies, particularly CEMS, are critical for enhancing the accuracy of carbon emission data, advancing carbon reduction efforts, and addressing climate change. The research on different approaches under specific constraints and limitations, will promote an effective carbon management and reduction. However, in the field of low-carbon research, there are no official or conventional definitions of the technologies for obtaining carbon emissions data from different energy systems. These methods involve different research fields, and in some references, "carbon metering" is used interchangeably with "carbon accounting", "carbon monitoring" and "carbon measurement" [6]. Prior to delving into a detailed exploration of various carbon emission quantification technologies, it is essential to establish precise and academic definitions while circumscribing their usage.

Carbon accounting generally refers to calculating and verifying carbon emissions over a specific period for individuals or organizations. In comparison with tracking financial transactions in a bank account, carbon accounting involves calculating and recording GHG emissions from various sources, such as transportation, buildings, and industrial processes [7]. The carbon accounting method includes the emission factor method and material balance method. The emission factor method has a mature calculation system and sufficient theoretical basis, which is the most commonly used. The IPCC's Guidelines for National Greenhouse Gas Inventories define emission factor as the characteristic GHG emissions per unit of production or consumption activity [3]. The basic principle of the material balance method is the law of conservation of mass, which states that the input of materials equals the sum of the output and the loss of materials [8]. The implementations of carbon accounting method are heavily dependent on the accuracy and completeness. For example, production conditions, fuel types, and fuel combustion states are required to be accurate and comprehensive to cover the whole process of carbon emission activities. However, most small and medium-sized enterprises cannot record full industrial production activity data. Furthermore, the statistical facilities and data processing technologies are challenging to support the applications of the material balance method. The carbon monitoring method is using real-time monitoring equipment to measure the CO_2 emissions. Compared to carbon accounting, carbon monitoring focuses on analyzing and processing monitoring data through hardware technique, which emphasizes real-time tracking of emissions. The implementation of carbon monitoring method is widely coordinated with various technologies, such as remote sensing and environmental data sensing. The monitoring method directly measures the flow rate, flow, and concentration of GHGs in a specific environment through measurement devices recognized by relevant national departments. Based on the measurement data identified by the environmental protection department, the total amount of GHG emissions is calculated [9]. Carbon measurement involves the quantification of GHGs released into the atmosphere due to human activities during a specific timeframe, utilizing various data processing methods, including mathematical modeling, *etc.* [10]. Beyond the acquisition of precise measurement data, the emphasis in carbon measurement lies in the prudent data management necessary for accurate carbon emissions determination. The process unfolds sequentially, commencing with the collection of monitoring data, followed by the subsequent data processing over a designated timeframe. Consequently, carbon measurement provides a static representation of carbon emissions for a specific period. Carbon metering is a method that effectively counting the carbon emissions generated by energy entities, organizations, and enterprises during their industrial production activities in real-time, especially using approved quantification approaches and units. Carbon metering adopts equipment-preprocessed computational models to record and transfer the emission data accurately.

In the context of this article, "carbon accounting" is combining the recorded data of carbon-related activities from individuals, organizations, and enterprises, calculating the total carbon emissions through mathematical modeling or economic statistical methods [11]. "Carbon monitoring" emphasizes obtaining direct and real-time carbon emission data through monitoring facilities without processing. The principal distinction between "carbon measurement" and "carbon metering" resides in the temporal sequence of monitoring data acquisition and processing. Carbon metering technology entails the establishment of a predefined processing model, direct monitoring of data inputs, and real-time calculation within metering facilities to derive dynamic carbon emission results. The monitoring method has fewer intermediate steps in its implementation process than carbon accounting methods, and providing dynamic data compared to the carbon measurement [12].

In terms of accuracy and continuity, real-time monitoring data demonstrates superior performance when using professional gas detection equipment and systems. For instance, the Neurath coal-fired power plant, operated by Rheinisch-Westfälisches Elektrizitätswerk (RWE), implemented an Internet of Things (IoT)-based carbon emission monitoring system to enhance carbon management efficiency. This system employs high-precision CO_2 sensors installed within chimneys and exhaust ducts, enabling real-time monitoring of CO_2 concentrations in emissions. The data is continuously transmitted to a cloud platform via wireless networks for storage and analysis [13]. By integrating machine learning algorithms, the system can predict high-emission trends and automatically issue alerts. During high-emission risk periods, operators are able to reduce emissions by optimizing fuel supply rates and adjusting combustion temperatures [14,15]. Through this system, the Neurath power plant achieved approximately a 15 % reduction in carbon emissions. The system automatically generates carbon emission reports, which are regularly submitted to the European Environment Agency (EEA) to ensure the accuracy and transparency of emission data [16]. Additionally, the Los Angeles city government compiles an annual carbon emissions inventory, covering major sectors such as buildings, transportation, and industry, to meet the carbon reduction targets [17]. The accounting process in Los Angeles integrates data from local energy companies and the transportation department, referencing the latest emission factors provided by the California Air Resources Board (CARB) to ensure the accuracy and policy relevance of the calculations [18]. However, studies indicate that, as the emission factor method relies solely on estimations, its carbon emission results tend to be approximately 5 %–30 % higher compared to real-time monitoring data. Consequently, the average discrepancy in data accuracy between carbon monitoring and accounting methods can reach up to 17 %. The carbon monitoring method seems to be a new direction in the industrial and scientific research for carbon emission reduction due to its real-time effectiveness and intuitive monitoring data. The relationship and research logic for carbon emissions and its quantification methods is illustrated in Fig. 1. Carbon metering involves the procedures for accounting for carbon emissions and monitoring techniques. These two components collaborate and mutually reinforce each other to provide the data support needed for the ultimate carbon quantification. In terms of carbon monitoring for fixed sources, CEMS is currently the predominant method. The main work of this article includes comparing and discussing the concentration monitoring devices and their related practical implementations, which will offer valuable references for researchers conducting future studies in this field.

This review paper examines carbon metering technologies for different energy systems, providing a critical analysis of the state of the art in carbon emission quantification technologies. Section 2 outlines the methodology. It introduces the bibliometric tools and corresponding databases used in this study. In Section 3, we explore commonly employed carbon accounting techniques for both stationary and mobile emission sources. Section 4 serves as the central focus, narrowing in on stationary sources of emissions. It conducts a comprehensive bibliometric analysis to identify the cutting-edge advancements in carbon monitoring technology, with particular emphasis on the technological intricacies of Continuous Emission Monitoring Systems (CEMS). Section 5 delves into the examination of gas concentration detection technology, and explores hardware-based technologies, which forms the core of CEMS.

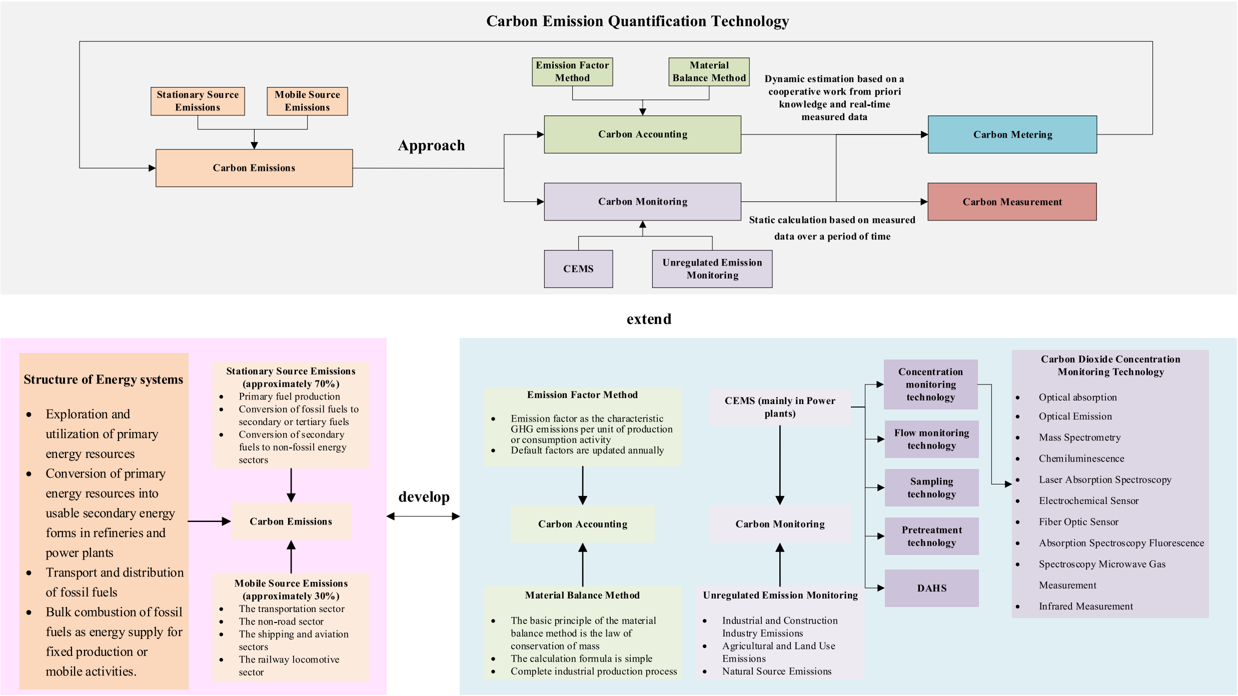

Fig. 1. Structural relationship diagram of carbon emissions.

Based on the CiteSpace bibliometric tool and combining expertise from fields such as environmental science, engineering, and data analytics, we offer a holistic perspective on the complexities of carbon monitoring and accounting. Our contributions lie in synthesizing the latest advancements, identifying critical gaps in the current literature, and offering insights into emerging trends. Table 1 in the article presents the abbreviations used. In Section 6, we conclude and offer recommendations for further research.

2. Methodology

In this study, we employed Citespace visualization tool version 6.1.6.R4 SE (64-bit) to conduct a literature analysis for the research issues, the standard for selecting references covers six elements: keywords, authors, journal categories, research fields, publication years, and countries/regions. The academic journals and conference papers were the main selection objects, and no explicit rules or constraints on journal ranking in the screening process. The searching fields included environmental science, engineering applications, energy, economics, and social sciences. The databases used for reference include Web of Science, ScienceDirect, OnePetro, SpringerLink, EV Compendex and IEEE/IEE Electronic library. The search primarily focused on English-language publications, including peer-reviewed academic journal articles, international patents, conference papers, books, and international standard methods. The search period spanned from 2010 to 2024 and the retrieval methods included free-text and subject-heading searches.

The results of the article filtering showed that most scholars mainly related to the issues of carbon emission monitoring, CEMS systems, CO2 concentration monitoring technology, climate change, and greenhouse effects. Three distinct research domains were estimated as the research objectives: carbon monitoring technology, CEMS, and CO2 concentration monitoring technologies. Carbon monitoring technology serves as the overarching term, encompassing all technologies aimed at quantifying carbon emissions across various sources and sectors. This keyword is chosen to highlight the fundamental theme of the paper, which is the advancement of precise carbon monitoring as a crucial tool for supporting carbon reduction and climate change mitigation. CEMS is a subset of carbon monitoring technologies that refers to a widely used method for monitoring emissions from fixed sources in real-time. By including CEMS as a keyword, we emphasize the paper's focus on direct, hardware-based monitoring methods, especially in industrial and energy sectors, where fixed-source emissions are a significant contributor to overall carbon output. CO_2 concentration monitoring technologies narrows the scope further to the specific measurement of CO_2 levels, which is central to accurately quantifying greenhouse gas emissions. This keyword underscores the paper's emphasis on the technical approaches and innovations in directly measuring CO_2 concentration, thus providing more accurate and immediate emission data than traditional carbon accounting. Recognizing the relevance and extensive applicability of CEMS technology to various gases, it entails the development of sophisticated hardware components and sensors dedicated to monitoring and quantifying emissions from stationary sources. The precise detection and measurement of CO2 concentrations constitute pivotal elements within the CEMS framework. Thus, within the context of CEMS, research endeavors are directed towards enhancing hardware design attributes, which are indispensable for achieving accurate CO2 detection and analysis. The CO2 concentration monitoring technologies, in turn, contributes significantly to the advancement of emission monitoring capabilities.

A total of 190 articles were selected after using "carbon emission monitoring technology" as the subject heading, while 125 and 214 articles were selected after using "CMES" and "concentration monitoring technology" as the subject headings, respectively. In order to improve the systematic and academic depth of the research method, the selected academic journals were further grouped and classified in the process of literature analysis. Based on the above three groups, the journal categories are divided into environmental science, Energy engineering, monitoring technology and climate policy. Priority is given to high-impact journals and core journals according to impact criteria to ensure the authority and representativeness of citations. By combining the keyword network map generated by CiteSpace tool and co-citation analysis, this study verified the rationality of journal grouping, and further revealed the high-frequency keywords, development trends and core contributions of various fields of research. "carbon emission" and "monitoring technology" are the core keywords in environmental science journals, reflecting the importance of carbon monitoring in environmental impact assessment. High-frequency keywords such as "CEMS" and "fixed source" in energy engineering journals highlight the application advantages of fixed emission source monitoring technology in the industrial field; The research focus of monitoring technology

Table 1
The abbreviations list.

Abbreviation	Full name
CDMA	Code Division Multiple Access
CEMS	Continuous Emission Monitoring System
DAHS	Data acquisition and handling system
GAW	Global Atmosphere Watch
GPRS	General Packet Radio Service
LED	Light Emitting Diode
LLR	Line of Least Resistance
MGGRA	Midwestern Greenhouse Gas Reduction Accord
NDIR	non-dispersive infrared technology
PSTN	Public Switched Telephone Network
RGGI	Regional Greenhouse Gas Initiative
SSPs	Shared Socioeconomic Pathways
VLM	Virtual logit matching
WMO	World Meteorological Organization

journals focuses on "sensor development" and "real-time CO_2 concentration monitoring", indicating the key role of sensor technology in accurate monitoring. Through the above grouping and classification analysis, this study systematically collates the literature on carbon monitoring technology and constructs the framework of core journals in different research fields, which not only reveals the development context of carbon monitoring technology, but also provides clear direction and theoretical support for future research. Additionally, the reference information in CiteSpace is iterated and compared through Python programming to obtain the most representative references worth discussing, as listed in Appendix. The highest priority is the number of citations, followed by the field and publication, and finally, the country. This paper focuses on the most frequently cited references in the search results. In terms of the research field, the monitoring and environment fields are considered significantly, followed by the chemistry and biology fields, *etc.* The journal category has the priority for different types of articles, followed by academic conference papers, and finally other types of publications. According to the Citespace national/regional cooperation research map, countries with more relevant studies and concentrated research topics are significantly discussed.

3. The current implementations of the carbon accounting method

3.1. Carbon accounting for stationary emissions source

The GHG emissions generated by stationary sources mainly come from the energy, manufacturing, and construction industries [19–21]. Currently, the carbon emission factor method is most commonly used to account the carbon emission from stationary emission sources. Yuanbo Geng, Ziteng Wang, and Leisheng et al. [22] conducted an extensive research study on Chinese cement production, employing the carbon emission factor methodology. Their investigation, which encompassed data derived from more than 100 newly New Suspension Preheater (NSP) kiln production lines in China, resulted in the refinement of carbon emission factors within the cement production process. Zhi Cao et al. [23] utilized the carbon emission factor approach to analyze carbon emissions within real cement production processes. Their research involved the enhancement of a factory-level database encompassing 197 cement production lines across 21 Chinese provinces, varying in production capacities. Kun Lu and Yubing Zhang et al. [24] focused on the construction industry to address the lack of comprehensive carbon emission factor databases in the Chinese construction sector. They established the Chinese construction industry carbon emission factor database for calculating carbon emissions in the construction industry. Lixue Chao et al. [25] introduced an advanced life cycle assessment (LCA) framework tailored to assess the carbon emissions associated with precast concrete column construction. Expanding upon conventional carbon emission factor calculation methods, their approach innovatively incorporates the evaluation of carbon emissions during vehicle transportation processes. Furthermore, they adopted the consumer lifestyle approach to estimate the carbon emissions attributed to construction workers. In 2015, the U.S. Environmental Protection Agency (EPA) reported that carbon emissions from the power industry were 1.97 billion tons, accounting for 29 % of the total carbon emissions in the United States. It decreased by 11.3 % compared to the carbon emissions from the power system in 2011 [26–28]. The decentralized carbon reduction management system plays a dominant role,but may lead to unfair carbon reduction quotas. For example, Regional Greenhouse Gas Initiative (RGGI) stipulates that the carbon emission quota for power plants in the ten states in the northern region from 2009 to 2011 is 188 million tons per year. In 2009, power plants in the region only emitted 123 million tons. The forecast data shows that until 2030, the regional carbon emissions will be controlled below the limit of 188 million tons [29]. The steel industry in China is the most applied field of carbon accounting [30,31]. According to the Corporate Social Responsibility (CSR) reports released by China Hualing Iron & Steel Co., Ltd., Jiangsu Shagang Group Co., Ltd., and United States Steel Corporation., the CO2 emission estimated by the carbon accounting method is shown in Table 2.

The research on industrial carbon emissions mainly focuses on the development of more mature large-scale industries such as steel, building materials production plants and electric power industry. These large industrial entities have complete and mature production processes, have the conditions to use the emission factor method, and the carbon emission data obtained through carbon accounting is close to the reality, which has a guiding role in the development of carbon emission reduction system for industrial entities. However, the application of carbon accounting methods in the quantification of carbon emissions in large industrial bodies has always been unable to determine the accuracy, and the emission factors used are often the annual data released by governments. Most of the studies mentioned above mainly use different ways to refine the carbon activities and carbon footprint of industrial production links, obtain

Table 2

Total carbon emissions reported by Steel Group Co., Ltd.

China Hualing Iron & Steel Co., Ltd			
Total CO2 Emissions Disclosure by Year	**2020 (in metric tons)**	**2019 (in metric tons)**	**2018 (in metric tons)**
Total CO2 Emissions	62,337,319	46,512,459	46,869,248
Unit CO2 Emissions per ton of steel	1.69	1.67	1.78
Jiangsu Shagang Group Co., Ltd			
Total CO2 Emissions Disclosure by Year	**2020 (in metric tons)**	**2019 (in metric tons)**	**2018 (in metric tons)**
Total CO2 Emissions	36,004,208	35,773,626	32,130,430
Unit CO2 Emissions per ton of steel	0.98	1.28	1.22
United States Steel Corporation			
Total CO2 Emissions Disclosure by Year	**2020 (in metric tons)**	**2019 (in metric tons)**	**2018 (in metric tons)**
Total CO2 Emissions	71,098,307	72,705,904	66,685,877
Unit CO2 Emissions per ton of steel	1.93	1.98	1.88

short-term carbon emission factors, for the improvement of the Carbon Accounting.

Mobile emission sources are GHG emissions generated during transportation activities, such as road and non-road transport, railway locomotives, shipping and aviation [32]. The GHG emissions from the road transport sector account for about 84 % of the total emissions from mobile sources, while the non-road sector only contributes 0.3 % of the total emissions [33]. The carbon measurement for mobile emission sources in the road transport sector, represented by the highway department, are generally divided into fuel combustion and driving distance methods [3]. Hatem Abou-Senna and Essam Radwan et al. [34] conducted an in-depth environmental assessment of vehicle operations along Interstate 10 in Orlando, Florida. Their investigation encompassed an analysis of four distinct methodological approaches, evaluating their individual impacts on the anticipated emissions of GHGs and other harmful pollutants. The fuel combustion method is used to calculate CO2 emissions, while the driving distance method with information on vehicle type and road type is more suitable for calculating CH_4 and N_2O emissions [35]. The non-road sector mainly includes agriculture, forestry, construction, and maintenance-related transportation departments [36].

The proportion of GHG emissions from the railway locomotive sector in mobile emission sources is less than 1 %. The carbon emissions generated mainly come from diesel combustion, electricity supply, or steam power [37]. For the shipping and aviation sectors, GHGs produced by shipping and air transport are roughly the same [38]. When using large ocean-going cargo ships for fossil fuel transportation, it is necessary to consider the carbon escape emissions caused by improper storage or placement of fossil fuels during transport [39]. The GHG emissions generated during air transportation are from fuel combustion and aviation gasoline [40]. Due to the unique nature of the work area in the aviation transportation sector, 70 % of hydrocarbons and CO2 are emitted in high-altitude airspace above 10,000 m and are excluded from the carbon accounting system [41]. In addition, due to the confidentiality of military aircraft and ship models and the difficulty of obtaining fuel data for related military equipment, estimates of GHG emissions from military aviation are only based on limited data, and rough judgments are made and even ignored. Rough carbon accounting methods are used for both civil aviation and civil shipping [42].

Mobile emission sources are larger and more dispersed than stationary [43]. The error range between the calculated and actual values can be controlled within 2 % when estimating the road transport sector's carbon emissions using national emission factors. However, other types of mobile emission sources, such as ships and aircraft mentioned above, are susceptible to environmental factors, and the emission profile is unclear, making the accuracy of carbon accounting methods difficult to assess. Using carbon accounting methods to obtain the GHG emissions from the mobile section is more challenging in controlling accuracy and timeliness.

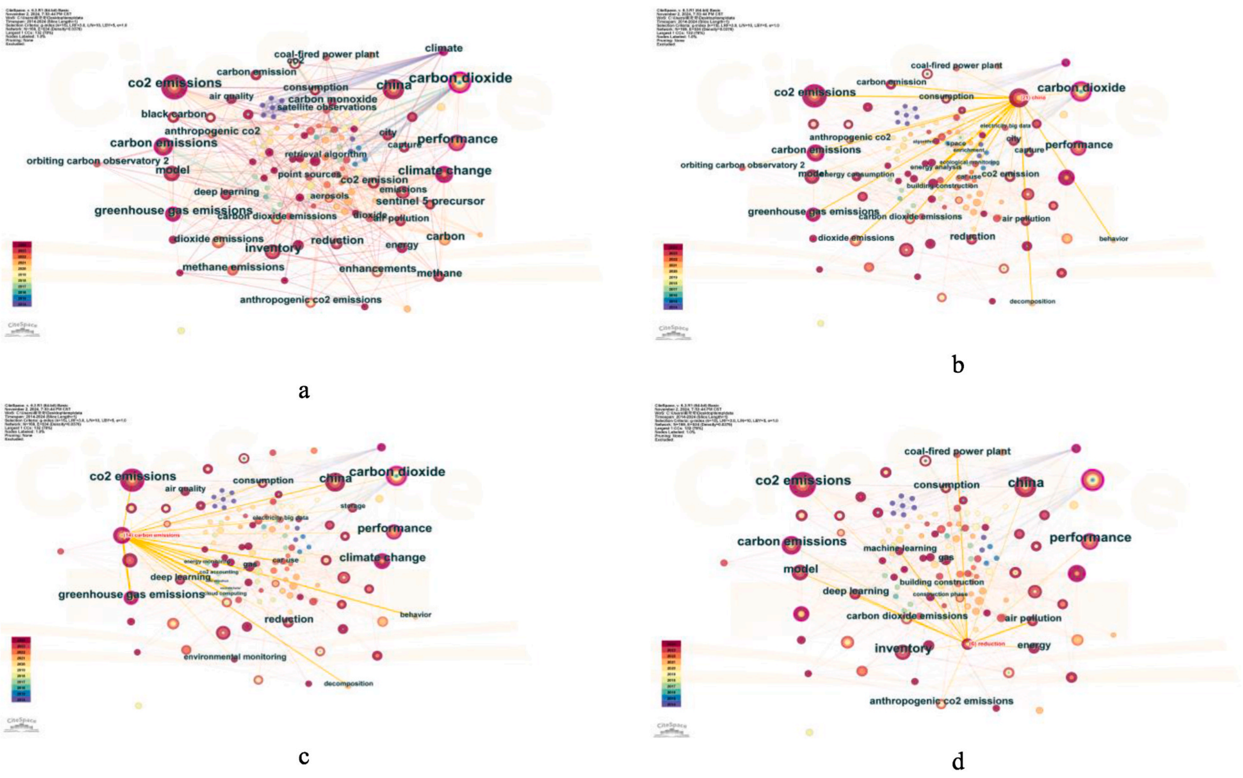

Fig. 2. CiteSpace keyword co-occurrence network map of carbon monitoring.

4. Carbon monitoring technology for stationary emissions sources

4.1. Carbon monitoring technology bibliometric analysis

With an extensive improvement of gas detection technology, monitoring methods have increasingly gained attention from the industrial and academic research fields due to their advantages of intuitive monitoring results, strong real-time performance, fewer intermediate links, a high degree of automation, and less human interference [44,45]. In terms of CiteSpace literature analysis, it involved 212 academic publications in the carbon monitoring technology field in the past decade. The CiteSpace keyword co-occurrence map of carbon monitoring technology is shown in Fig. 2. The value of Modularity Q in Fig. 2 is 0.7642 (>0.3), indicating that the keyword clustering structure is strong and the clustering effect obtained is good. The Silhouette S value is 0.9518 (>0.5), with a value close to 1 indicating high average homogeneity of the network and reasonable clustering results. The node size corresponds to the frequency of the keyword's appearance in the paper. Larger nodes signify higher keyword frequency. The connecting lines between keywords show that research conducted around the keyword in a specific year has traversed various fields.

Fig. 2(a) provides a comprehensive overview of the multidimensional research framework within the field of carbon emission monitoring, illustrating the interconnections between monitoring technologies, greenhouse gas control, algorithm applications, and global climate governance. The keywords highlighted in the figure indicate that carbon emission monitoring extends beyond carbon dioxide, encompassing integrated monitoring of various greenhouse gases to enable a more holistic assessment and control of climate change drivers. The structure of multipollutant co-monitoring suggests an integrated trend within carbon monitoring research. Fig. 2(b) presents a keyword co-occurrence map centered on "China," derived from the framework in Fig. 2(a). This map highlights distinct regional characteristics in the study of "carbon emission monitoring technology," underscoring China's pivotal role in global climate change and greenhouse gas reduction efforts over the past decade. The close association of themes like "carbon dioxide," "CO2 emissions," "carbon emissions," and "greenhouse gas emissions" with "China" suggests that research on carbon emission monitoring in China addresses not only CO_2 emissions but also encompasses comprehensive greenhouse gas monitoring. This approach highlights a focus on both CO_2 control and the broader environmental and climatic impacts of other greenhouse gases. The prominent connections to nodes such as "coal-fired power plant," "building construction," and "energy consumption" indicate that carbon emission monitoring research is particularly relevant to sectors like coal-fired power, construction, and energy use. Furthermore, nodes like "big data," "ecological monitoring," and "energy analysis" reveal a trend toward integrating advanced tools, such as big data, ecological monitoring, and energy analysis, to enhance timeliness and provide data support for source analysis, spatial distribution assessments, and trend forecasting of carbon emissions. In addition, nodes such as "decomposition," "behavior," and "ecological enrichment" suggest potential future research directions, including micro-level studies on carbon decomposition processes and the impact of human behavior on carbon emissions. Fig. 2(c) presents a keyword co-occurrence map centered on "carbon emissions," based on the framework in Fig. 2(a). As the central node, "carbon emissions" is closely linked to key themes like "CO_2 emissions," "greenhouse gas emissions," "China," "climate change," and "reduction," indicating that carbon emission control has become a central issue in addressing climate change and environmental protection. Notably, nodes such as "deep learning," "big data," "cloud computing," and "electricity" highlight the ongoing trend towards intelligent and refined development in carbon monitoring technologies. For example, the integration of deep learning and big data enables real-time processing and trend forecasting of carbon emission data. Additionally, cloud computing enhances data processing efficiency, allowing carbon emission monitoring to be automated on a larger scale, thereby broadening its application range. The strong associations among nodes like "consumption," "energy monitoring," "gas," and "reduction" suggest that energy consumption and gas emissions are primary sources of carbon emissions. By focusing on energy

Table 3
Top 20 high-frequency keywords from CiteSpace bibliometrics analysis of carbon mornitoring

Number	Frequency	Centrality	keyword
1	21	0.19	co2 emissions
2	21	0.09	China
3	16	0.27	carbon dioxide
4	14	0.13	carbon emissions
5	12	0.11	performance
6	12	0.14	climate change
7	10	0.05	inventory
8	10	0.06	model
9	9	0.12	greenhouse gas emissions
10	8	0.02	dioxide emissions
11	8	0.04	emissions
12	6	0.03	reduction
13	6	0.04	carbon
14	6	0.05	co2
15	5	0.04	methane emissions
16	5	0.02	methane
17	5	0.02	capture
18	5	0.03	deep learning
19	5	0.02	air pollution
20	5	0.02	energy

sectors, including natural gas and coal-fired power plants, more precise carbon emission control can be achieved at the source. In addition, nodes like "climate change" and "behavior" underscore that carbon emissions are not only directly linked to climate change but also closely tied to human consumption patterns and energy usage behaviors, further emphasizing the importance of societal behavior changes in the carbon reduction process. Fig. 2(d) illustrates a keyword co-occurrence map centered on "reduction" within the context of "carbon monitoring technology." "reduction" is closely linked to key themes such as "carbon emissions," "CO_2 emissions," "air pollution," and "inventory," underscoring that carbon reduction is central to addressing climate change and achieving sustainable development goals. The nodes "energy," "consumption," and "building construction" indicate that high-energy-consumption sectors, particularly the construction industry, are primary contexts for current carbon reduction research. The nodes "energy," "consumption," and "building construction" indicate that high-energy-consumption sectors, particularly the construction industry, are primary contexts for current carbon reduction research. Additionally, the strong association with the "air pollution" node suggests that carbon monitoring technologies not only facilitate greenhouse gas control but also contribute positively to air quality improvement and ecological sustainability.

The thickness of these lines reflects the strength of correlation, with thicker lines indicating stronger interconnections between research issues. From 2014 to 2016, the research concentrated on carbon emissions, CO2 capture technology, and carbon monitoring technology. From 2018 to 2019, various countries developed low-carbon economies, and scholars in manufacturing, engineering, and energy-related fields focused on GHG emission monitoring, carbon cycle, atmospheric inversion, and carbon emission models. The issues of environmental changes, CO2 emissions, quantifying air pollution levels, carbon emission monitoring methods, and energy system carbon consumption have continued to rise in popularity since 2021. Table 3 shows the top 20 keywords with the highest frequency in Fig. 2. Among them, the nodes such as " carbon dioxide ", " co2 emissions ", " greenhouse gas emissions "and " china " are larger, which means that they occur more frequently in the reference.

4.2. CEMS technology overview

With the continuous deepening of environmental awareness, countries worldwide have successively promulgated mandatory regulations requiring the installation of CEMS for monitoring the emissions of volatile organic compounds (VOCs) from fixed emission sources in the energy industry. The CEMS can integrate different types of gas detection modules according to monitoring requirements [46,47], which makes it possible to monitor carbon emissions in real time. The main components of CEMS include 1) flue gas concentration monitoring equipment; 2) flue gas flow rate monitoring equipment; 3) sampling equipment; 4) pretreatment equipment; and 5) a flue gas Data Automatic acquisition and Handling System (DAHS). Concentration is a parameter that directly reflects gas emissions. The gas concentration monitoring technology as the core to achieve accurate quantification of the monitored gas, will be discussed later. The gas flow rate monitoring technology has become mature, with a wide variety of implementations depending on their working environment [48–50]. Table 4 serves as a primary function to compare and evaluate the suitability and performance of several common traffic monitoring techniques, aiming to provide a clear and systematic comparison framework. This helps to show the basic characteristics of each technology and reveals the advantages and limitations of different technologies in specific application scenarios, thus providing theoretical basis for decision-makers to choose suitable traffic monitoring technologies. In the table, the advantage of the vortex flowmeter lies in its simple structure, durability, and high dynamic response capability, but its performance is susceptible to fluctuations in fluid properties. Gas turbine flowmeter is characterized by its high precision and fast response, but it has high requirements for the stability of gas flow rate and gas purity. The thermal gas mass flowmeter has a wide measuring range and a fast response speed, but it is very sensitive to the temperature, pressure and composition of the gas. In the case of high demand for high precision gas flow measurement, gas turbine flowmeters are suitable for use in environments with strict control of flow rate stability due to their high precision and fast response characteristics. Despite the high accuracy and response speed of gas turbine flowmeters, their sensitivity to flow velocity distribution and gas purity limits their effectiveness in certain complex applications. If faced with unstable flow velocity or gas containing particles, vortex flowmeters or thermal gas mass flowmeters may be more suitable for gas flow measurement.

The core role of Table 5 in this paper is to compare and evaluate the advantages and disadvantages of the two main sampling techniques, the in-situ sampling equipment and the extraction-type sampling equipment, so as to provide a clear reference frame for selecting the appropriate sampling method. Through intuitive comparison, the table details the installation methods, advantages and disadvantages of the two technologies, providing key decision-making support and theoretical basis for technology selection according to different environmental requirements in actual engineering, to ensure that the final sampling scheme can meet the accuracy and stability requirements of environmental monitoring. The differences between in-situ sampling equipment and extraction-type

Table 4
Comparison of flow rate monitoring technologies.

Technology	Advantages	Disadvantages
Vortex Flowmeter	Simple structure, strong durability, and high dynamic response	Vortex flowmeters can be influenced by the properties of the measured fluid, requiring stability in the flow characteristics. They may introduce some pressure loss in the system
Gas turbine flowmeter	High accuracy, fast response, strong pressure resistance"	Strict requirements for dynamic parameters such as gas flow velocity, requiring stable flow velocity distribution, high requirements for gas purity, unsuitable for flow measurement of gas containing particles and corrosive gases.
Thermal gas mass flowmeter	High accuracy, wide range of gas measurement, fast response speed"	Sensitivity to gas parameters, monitoring accuracy influenced by gas temperature, pressure, and composition, strict environmental requirements, susceptible to gas viscosity.

Table 5

Comparison of sampling technologies.

Classification	Installation method	Advantages	Disadvantages
In-situ sampling equipment	Directly installed at the sampling point in the flue.	It simplifies the installation process and allows for real-time acquisition of flue gas data, providing timely and accurate information.	It is susceptible to interference from water vapor and is suitable for specific flue gas conditions. The selection of sampling point locations can be challenging.
Extraction-type sampling equipment	Gas is extracted and transferred to the analyzer through a probe in the extraction-type sampling equipment.	The extraction-type sampling equipment eliminates interference from water vapor, has a wide range of practical applications, and offers flexibility in sampling locations.	Installation and maintenance are complex, and the extraction-type sampling equipment is prone to delays and hysteresis effects. During the sampling process, it may introduce additional interfering substances, which can affect the monitoring results.

sampling equipment are listed in terms of ease of installation, real-time data acquisition, interference factor control, etc., and the characteristics and applicable conditions of each technology are clearly analyzed [51,52]. In complex and changing environments, understanding the advantages and disadvantages of these technologies is important for optimizing monitoring systems. For example, in-situ sampling equipment is suitable for monitoring under specific smoke conditions due to its simple installation and real-time performance, but its universality is limited by its vulnerability to water vapor interference. Extraction-type sampling equipment is more suitable because it can avoid water vapor interference, but installation and maintenance is more complicated, and additional interference factors may be introduced in the sampling process. The influence of particulate matter in flue gas on GHG monitoring is important, it is necessary to process particulate matter before monitoring, which is pretreatment technology. The flue gas pretreatment equipment mainly includes sample filtration, dehumidification, and condensation equipment [53]. The analysis principles of particulate matter are classified into three categories: optical method, electrical method, and radioactive method. Integrating the flue gas data acquisition and processing system [54] The role of Table 6 in this paper is to show and compare the application of different DAHS (Data Acquisition and Processing systems) in various monitoring systems. By listing typical CEMS systems and their corresponding system components and recording data, the table provides the reader with a clear perspective to help understand the function and practical application of DAHS in different types of continuous emissions monitoring systems. The table not only shows the technical composition of each system, but also clarifies the recorded data type of each system in practical application, thus providing an important basis for selecting a suitable monitoring system and understanding its working principle. Table 6 details three common continuous emission monitoring systems (CEMS), their components and recorded data content. In CO_2 CEMS, DAHS work in combination with CO_2 concentration detectors and oxygen monitors to record the percentage of carbon dioxide (%CO_2); Flow CEMS is combined with flow monitor to record the volume flow of flue gas. The Humidity CEMS records the average hourly oxygen concentration (%) on a wet and dry basis using DAHS, continuous humidity sensors, oxygen analyzers and temperature and humidity lookup tables. These specific data provide basic information for understanding the application of different monitoring systems in environmental monitoring, and further emphasize the key role of DAHS as a core component in data acquisition and processing. In practical applications, CO_2 CEMS can monitor the CO_2 concentration in flue gas in real time by cooperating with CO_2 concentration detector and oxygen monitor, and data processing through DAHS, providing high-precision and timely emission data. However, CO_2 CEMS is greatly affected by changes in smoke composition and humidity, which may lead to measurement errors. Flow CEMS is mainly used to monitor flue gas flow, can calculate emissions in real time, has a flexible installation method, suitable for various emission sources, but its data may be affected by flow rate fluctuations and temperature changes, there is a certain lag. Humidity CEMS, combined with DAHS, humidity sensors, oxygen analyzers, and temperature and humidity lookup tables, can accurately measure the humidity and reflect the oxygen concentration in gases. This is especially important in environments where the humidity varies greatly. However, the stability of humidity sensors and the use of lookup tables may cause calculation delays in actual operations. CO2 monitoring based on CEMS is usually recorded in percentage form. DAHS is responsible for automatically collecting and processing relevant emissions data obtained from monitoring devices during designated periods [55]. After being processed by artificial intelligence algorithms and big data analysis, intelligent monitoring of carbon metering is achieved in both time and space dimensions, Fig. 3 shows that the carbon emission monitoring system consists of three core modules: data analysis module, monitoring scenario module and dynamic monitoring module. First, the Data Analysis function module provides a comprehensive statistical analysis and visual presentation of historical data on CO_2 and CH_4 emissions, revealing the contribution and changing trends of total emissions from different time periods and different emission sources such as combustion furnaces, discharge pipes, tailpipe treatment systems, and fuel storage leaks. This module not only supports the emission intensity analysis based on time series, but also provides quantitative

Table 6

Applications of DAHS.

Monitoring system	System components	Record data
CO2 CEMS	CO2 Concentration Detector, Oxygen Monitor, and DAHS	Carbon Dioxide Percentage (%CO2)
Flow CEMS	Flow Monitor and DAHS	Flue Gas Volume Flow Rate
Humidity CEMS	DAHS, Continuous Humidity Sensor, Oxygen Analyzer, and Temperature/Humidity Lookup Table	Average hourly O2 concentration (%) on a wet and dry basis

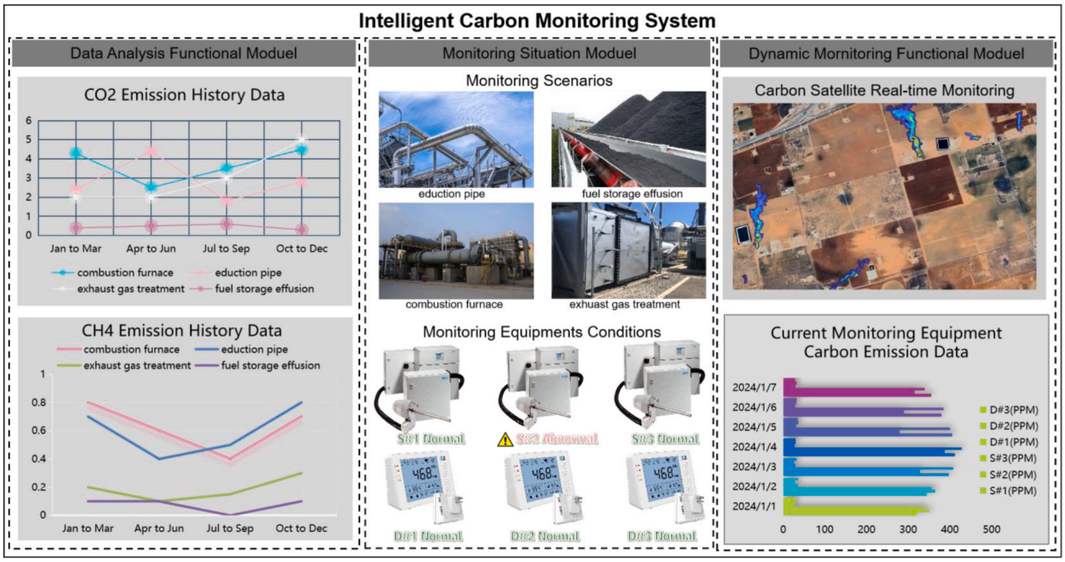

Fig. 3. Intelligent carbon monitoring system.

basis for the subsequent carbon emission prediction, emission reduction target setting and policy optimization. Secondly, the monitoring scene module presents the operating environment and status of the monitoring equipment by combining the actual industrial field image with the real-time status monitoring of the field equipment, and ensures the real-time and accuracy of the monitoring data. The module can reflect the geographical distribution of carbon emission sources and the working status of the equipment, and detect whether there is any abnormality in the equipment in real time, so as to improve the reliability of the system and ensure that the interference factors that may exist in the data collection process are effectively controlled. Finally, the dynamic monitoring function module relies on the carbon satellite remote sensing monitoring technology to provide real-time monitoring data of carbon emissions in a wide range of areas, and displays the carbon emission concentration of each monitoring device through the equipment monitoring data, so as to realize the spatiotemporal dynamic tracking of carbon emissions. This module can not only reflect the geographical distribution changes of carbon emissions in real time, but also identify high-emission areas, provide accurate emission source positioning, and provide key data support for carbon emission governance and decision-making. Through the collaborative work of these three modules, the system not only realizes the comprehensive monitoring of carbon emissions, but also enhances the visualization ability of data, and provides multi-dimensional, real-time and accurate decision support for carbon emission reduction management.

4.3. CEMS technology bibliometric analysis

Concentration monitoring equipment is one of the crucial components of continuous emissions monitoring systems (CEMS), which is used for the real-time, continuous, and accurate measurement of pollutant concentrations in flue gas. A bibliometric analysis of 125 academic papers on CEMS technology over the past decade was conducted. Fig. 4 is the CiteSpace co-occurrence shows a total of 183 nodes with 117 connections and a network density of 0.027. Table 7 shows the top 20 keywords with the highest frequency in Fig. 4. For the top three keyword co-occurrence frequency is "trends, "air pollution", and "air quality". In terms of centrality, "air pollution" has centrality value with 0.09 are the most important Bridge of the whole keyword co-occurrence network. It can be concluded that the research on CEMS related to air pollution and trends.

Fig. 4(a) presents a keyword co-occurrence map focused on the theme of Continuous Emission Monitoring Systems (CEMS) [56]. Based on node size, it is evident that "emissions," "continuous emission monitoring system," "trends," "control policy," and "atmospheric pollutants" occupy central positions. By filtering out other keywords, these core nodes can be analyzed individually to provide a detailed understanding of their roles [57]. Fig. 4(b) illustrates the keyword co-occurrence relationships within the research context of CEMS, with "emissions" as the central node. The larger nodes connect multiple subfields, with the thick connection line between "air pollution" and "emissions" indicating a high-frequency co-occurrence relationship [58]. A color-coded timeline reveals that early studies primarily focused on foundational monitoring methods such as "classification" and "flux measurements," while recent research has shifted toward topics like "carbon dioxide" and "continuous emission monitoring system." This evolution suggests a transition in the field from traditional pollutant monitoring to greenhouse gas monitoring, with a preference for comprehensive monitoring technologies like CEMS [59]. Fig. 4(b) also displays the cluster structure and interrelations among different subfields. For instance, branches centered on "carbonyl sulfide cos," "carbon dioxide," and "fluxes" emphasize research on gas emission component analysis and flow measurements [60]. "Air pollution" and "climate change" nodes focus on the relationship between air pollution and climate change. Additionally, nodes like "dioxide" and "deforestation," located farther from the central node with fewer connections, represent research areas that have yet to form systematic frameworks, suggesting potential directions for future research [61]. Fig. 4(c)

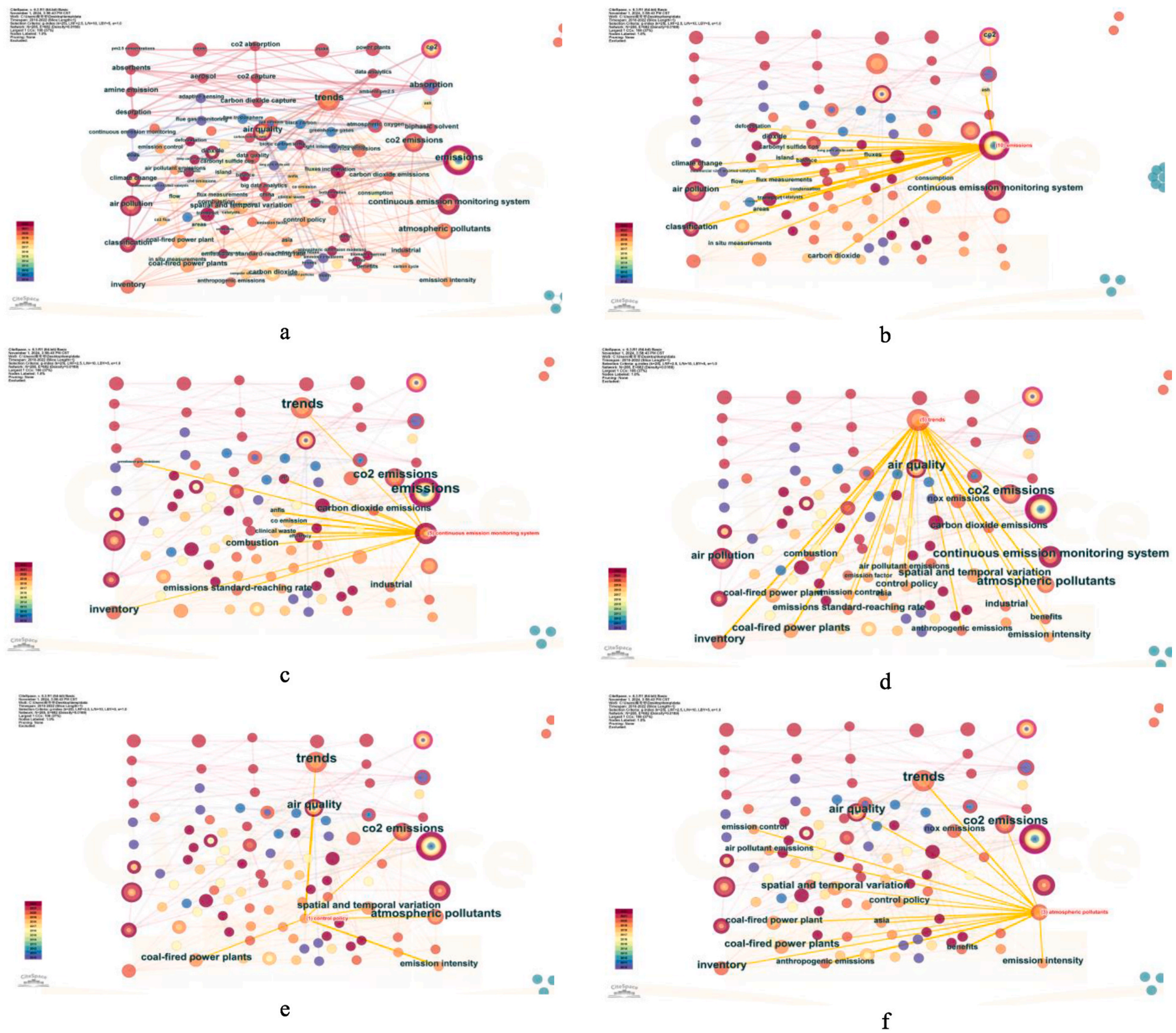

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Fig. 4. CiteSpace keyword co-occurrence network map of CEMS.

highlights the central role of the “continuous emission monitoring system” (CEMS) in research. The connections among high-frequency nodes like “emissions,” “carbon dioxide emissions,” and “CO₂ emissions” clearly underscore the importance of CEMS technology in carbon emission studies [62]. Additionally, nodes like “combustion” and “industrial” emphasize the direct impact of combustion processes and industrial activities on emissions, while the “emissions standard-reaching rate” node indicates a focus on standardized control, which is essential for enforcing environmental regulations. From a temporal evolution perspective, the “inventory” node appears darker, showing that early research focused primarily on constructing and managing greenhouse gas emission inventories. In contrast, the lighter-colored “trends” node indicates that recent research has shifted toward analyzing emission trends. Fig. 4(c) also reveals several cluster structures. For example, a tight cluster between “greenhouse gas emissions” and “carbon dioxide emissions” reflects the consistency between greenhouse gas and carbon emissions in the context of CEMS research [63]. Similarly, the cluster formed by “combustion” and “industrial” suggests that carbon emissions from combustion are central to industrial carbon monitoring. In addition, marginal topics such as "clinical waste" and "efficiency" suggest future exploration in the monitoring of medical waste emissions and monitoring efficiency [64]. Fig. 4(d) illustrates the keyword co-occurrence relationships within the CEMS research context, with “trends” as the central theme. Positioned at the center, the “trends” node is surrounded by nodes that indicate the development trajectory of related research [65]. For instance, the “spatial and temporal variation” node reflects the attention CEMS technology places on spatial and temporal changes, providing a multidimensional perspective for optimization. This underscores the importance of dynamic monitoring and forward-looking analysis [66]. Fig. 4(e) presents the research status of “control policy” as a central theme in the CEMS research field. The close network formed by “air quality” and “CO₂ emissions” nodes with “control policy” reflects a growing research focus on regulatory policies related to air quality and carbon dioxide emissions within the context of CEMS

Table 7
Top 20 high-frequency keywords from CiteSpace bibliometrics analysis of CEMS technology.

Number	Frequency	Centrality	keyword
1	10	0.15	emissions
2	7	0.02	emission
3	5	0.08	Continuous Emission Monitoring System
4	5	0.07	trends
5	5	0.06	air pollution
6	4	0.11	co2
7	4	0.05	air quality
8	4	0.02	co2 emissions
9	3	0.08	absorption
10	3	0.03	classification
11	3	0.01	atmospheric pollutants
12	2	0.02	atmospheric oxygen
13	2	0.02	coal-fired power plants
14	2	0.02	power plants
15	2	0.02	incineration
16	2	0.01	gas sensors
17	2	0.01	dioxide
18	2	0.01	climate change
19	2	0.01	coal-fired power plant
20	2	0.01	data quality

technology [67]. From a temporal perspective, the “coal-fired power plants” node indicates that early research focused on emissions control from traditional energy sources. In recent years, however, research has gradually shifted toward the “trends” node. This shift reflects the evolution of CEMS-based control policy research, with an expanding focus from source-specific control to broader trend prediction and management [68].

4.4. *The current application status of CEMS technology*

Developed countries have started early and proliferated gas detection equipment. CEMS technology is relatively mature. The United States has used carbon monitoring to measure carbon emissions in industrial areas. The U.S. government has required coal-fired power units to use CEMS to monitor carbon emissions since 1971. Data shows that the carbon emissions measured by CEMS monitoring technology accounted for more than 95 % of the total carbon emissions in the United States in 2015, with 73.9 % of the thermal power units equipped with CEMS for monitoring [69]. The E.U. uses both carbon accounting and carbon monitoring methods to measure carbon emissions from industries and requires coal-fired power plants with a production capacity exceeding 20 M W. to report carbon emissions accounting data [70,71] regularly. The European Commission launched the E.U. Emissions Trading System (EUETS) in 2005 to monitor carbon. More than 10,000 energy companies are involved, which cover more than 50 % of CO2 emissions in the E.U. About 140 coal-fired power plants in 22 European countries use real-time monitoring to achieve carbon measurement [72]. From the perspective of monitoring costs, the EUETS divides monitoring data quality into different levels, as shown in Table 8.

Academic research and industrial product development related to CEMS technology are mainly concentrated in China and the United States. Other countries, such as Canada, France, Germany, Italy, *etc.,* are also researching the application of CEMS technology. China has made the most significant research efforts in carbon monitoring technology [73]. China has successively established 16 national background monitoring stations since 2008. It includes 11 stations that achieved real-time monitoring of CO_2 and CH_4. Five monitoring stations completed the upgrading and transforming the GHG monitoring system in July 2021. The updated monitoring accuracy of CO_2 and CH_4 fully meets the requirements and indicators for global background observation proposed by the World Meteorological Organization/Global Atmosphere Watch (WMO/GAW). Furthermore, pilot GHG monitoring was conducted at the urban scale in 31 provincial capital cities during 2011–2015 [74]. In 2021, carbon monitoring pilot sites were established in 16 cities, including Tangshan, Shanghai, and Hangzhou, focusing on five key industries: thermal power, steel, oil and gas extraction, coal mining, and waste treatment. Several American companies primarily using CMES products have also launched engineering projects for CO2 emission monitoring. For example, MECHANICALSYSTEM, INCORPORATED designed and installed a CEMS for a wood-burning steam boiler. In this project, the BetaGuard particle monitor provided a better solution due to the presence of moisture, which prevented the use of continuous opacity monitoring systems (COMS). The CEMS includes an air flow monitoring device. The CMES dilutes

Table 8
Categorization of maximum allowable uncertainties for E.U. carbon emission enterprises.

Level	Types of Power Plants	CO2 Emissions (in metric tons per year)	Maximum Allowable Uncertainty for CEMS (in percentage %)
1	A1	<25000	±10
2	A2	25000–50000	±7.5
3	B	50000–500000	±5.0
4	C	>500000	±2.5

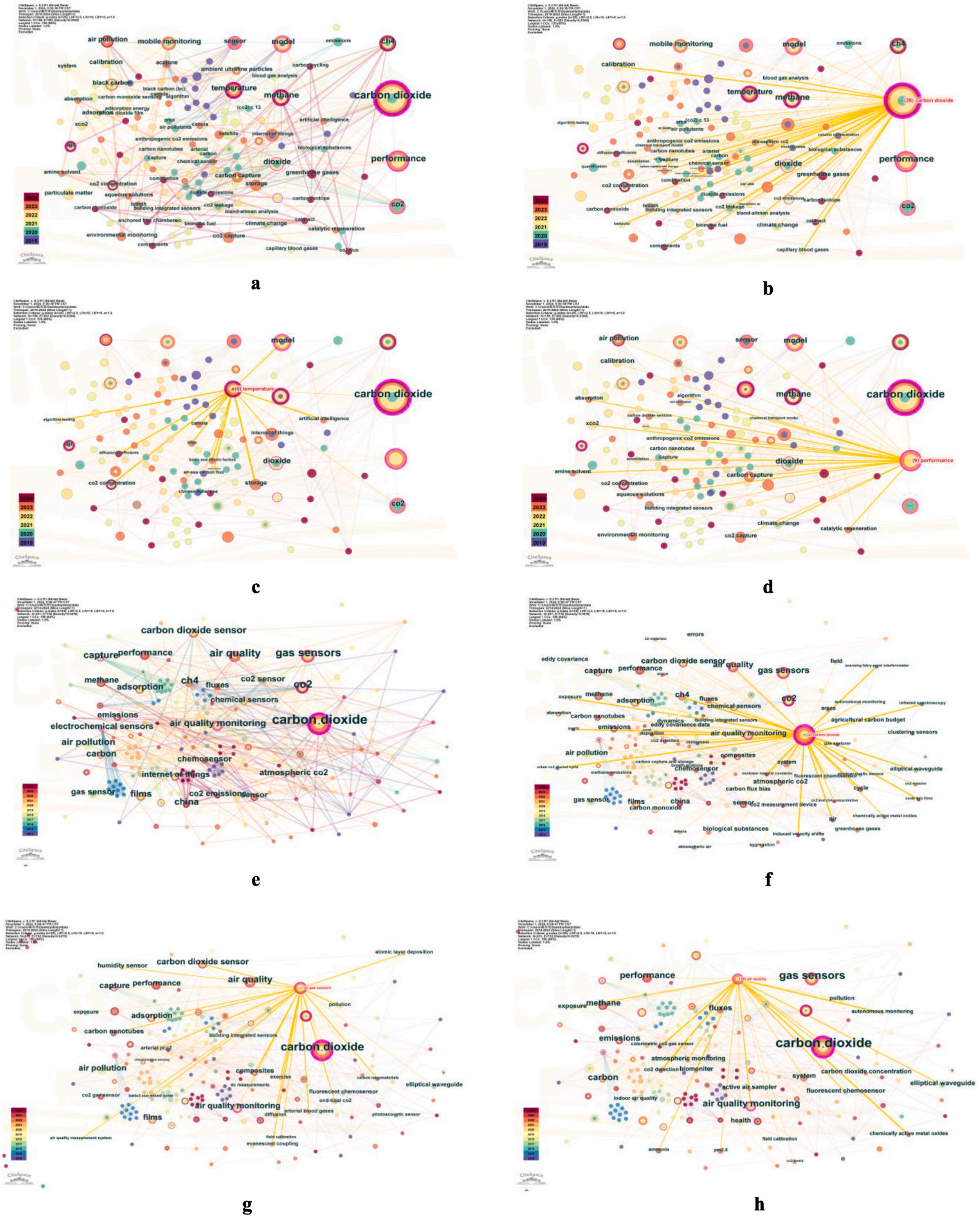

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Fig. 5. CiteSpace keyword co-occurrence network map of concentration monitoring technology.

CO_2, a BetaGuard particle monitor for reliable, real-time particle measurement, and a Virtual Logit Matching(VLM)technologies data acquisition system that provides emission analysis and supports regulatory reporting requirements [75]. The entire CEMS is certified according to EPA performance specifications to validate the installation and ensure compliance with regulatory requirements. Research on carbon monitoring devices in various countries mainly focuses on gas detection technology. It gradually develops into a universal carbon monitoring technique for different emission sources, combined with other advanced methods, such as big data.

Precision flow rate monitoring equipment faces challenges due to stringent environmental requirements. The technology is highly susceptible to variations in temperature and pressure, affecting its accuracy and reliability. The high-dynamic-response ability of the monitoring equipment becomes vulnerable when dealing with the flow characteristic. This limitation can lead to inaccuracies in flow rate measurements, hindering the technology's effectiveness in diverse gas flow scenarios. The composition of flue gases, containing different pollutants and particulate matter, and often have high temperatures and harsh chemical conditions. In terms of flue gas pretreatment technologies, the main challenge is to develop materials and technologies that can withstand these conditions while efficiently removing impurities. CEMS demands real-time monitoring. It requires pretreatment systems to operate swiftly and reliably, which provide accurate and timely data. Over time working may cause efficiency degrade of flue gas pretreatment systems due to fouling and corrosion, *etc.* Maintaining stable and high performance over extended periods is a significant concern for pretreatment technique for CEMS. For DAHS, the continuous monitoring of flue gas generates large volumes of data. Managing and processing the complex dataset efficiently pose a significant challenge. Moreover, the emissions data need to be processed in real-time for timely decision-making. Achieving quick and accurate analysis is crucial but demands sophisticated algorithms and computational power. The employment of multiple sensors to measure various emission gases requires integrating data from different sensors seamlessly and ensuring their coherence. Ensuring the quality and accuracy of the acquired data is essential. Calibration, drift correction, and error handling mechanisms are required to maintain the reliability of the data. With the increasing connectivity of monitoring systems, protecting the acquired data from cyber threats is crucial. Implementing robust cybersecurity measures is a continuous challenge.

5. The flue gas concentration monitoring technologies in CEMS

The precision of the concentration data acquired through monitoring has a direct impact on the efficacy and value of CEMS,and the flue gas concentration monitoring technology is the most critical and basic in CEMS. In order to gain a thorough understanding of the literature, we also identified reference materials centered around the core keywords ''CO2 concentration monitoring technology'' and ''CO2 concentration monitoring equipment'' for a bibliometric analysis using Citespace. These two keywords are intricately interconnected, embodying the theoretical framework and practical applications of monitoring methodologies, thereby constituting the fundamental research focus of CO_2 monitoring. In terms of commonality, both emphasize enhancing the real-time capabilities and accuracy of CO_2 concentration data to facilitate precise monitoring and regulation of industrial carbon emissions. The distinction lies in that ''CO_2 concentration monitoring technology'' prioritizes theoretical exploration and innovative approaches, including the suitability and precision of detection technologies as well as the optimization of data processing techniques and simulation algorithms. Conversely, ''CO2 concentration monitoring equipment'' places greater emphasis on hardware design and operational stability within industrial contexts, addressing practical considerations such as sensor selection, device longevity, and adaptability. By integrating research across these two domains, it becomes feasible to advance high-precision CO_2 emission monitoring from both theoretical innovation and equipment implementation perspectives.

Table 9
Top 20 high-frequency keywords in the CiteSpace of flue gas concentration monitoring technology.

Number	Frequency	Centrality	keyword
1	28	0.79	carbon dioxide
2	9	0.38	performance
3	8	0.17	temperature
4	7	0.19	model
5	7	0.16	methane
6	7	0.10	ch4
7	6	0.11	co2
8	6	0.10	mobile monitoring
9	5	0.16	dioxide
10	5	0.06	air pollution
11	5	0.01	black carbon
12	3	0.05	co2 concentration
13	3	0.03	particulate matter
14	3	0.03	storage
15	3	0.03	co2 capture
16	2	0.02	acetone
17	2	0.02	Atmospheric co2
18	2	0.02	calibration
19	2	0.02	system
20	2	0.02	sensitivity

5.1. *The flue gas concentration monitoring technologies bibliometric analysis*

The CiteSpace analyzed 182 academic papers published in flue gas concentration monitoring technology through last decade. Fig. 5 (a)–(d) and (e) to (h) are keyword co-occurrence maps with the theme of "carbon dioxide concentration monitoring technology" and "carbon dioxide concentration monitoring equipment" respectively. It shows a total of 815 nodes with 275 connections and a network density of 0.027. Tables 9 and 10 respectively shows the top 20 keywords with the highest frequency in Fig. 5 (a) and (e).

The keyword co-occurrence network map generated under the theme of "carbon dioxide concentration monitoring technology" elucidates the knowledge architecture and core research trajectories within this domain. Fig. 5(a) illustrates that "carbon dioxide" serves as the central theme in the context of "carbon dioxide concentration monitoring technology [76]," forming a dense network with pivotal nodes such as "temperature," "performance," and "chemical sensor." This highlights a concentrated focus on monitoring system performance, sensor technologies, and multi-dimensional joint monitoring of greenhouse gases [77]. Notably, advancements in sensor technology and model construction are crucial for achieving precise carbon dioxide concentration monitoring and dynamic forecasting, thereby influencing the stability and applicability of systems across various application scenarios. Fig. 5(b) further investigates the correlation between temperature fluctuations and methane emissions, underscoring the significance of integrating information related to "temperature," "methane," and other greenhouse gases in comprehensive multi-component greenhouse gas monitoring efforts. Fig. 5(c) emphasizes that temperature monitoring—bolstered by climate models, Internet of Things (IoT), and artificial intelligence (AI)—is progressively evolving towards intelligent real-time capabilities. The strong association between the “temperature” node with both “Internet of Things” and “artificial intelligence” indicates an increasing emphasis within the scientific community on enhancing precision and real-time analysis of climate data through cutting-edge technologies to facilitate long-term observation [36]. Fig. 5(d) depicts enhancements in monitoring system performance, particularly regarding improvements in sensor accuracy and algorithm optimization. The distribution surrounding the “performance” node suggests that data analysis algorithms alongside diverse monitoring methodologies play a significant role in augmenting measurement accuracy as well as emission reduction efficiency. Collectively, these maps reflect an emerging trend within the field of “carbon dioxide concentration monitoring technology,” which is gravitating towards high precision, multidimensionality, and intelligent solutions; they also imply potential breakthroughs ahead in areas such as sensor development, multi-gas joint surveillance, and overall system performance enhancement [66].

Under the research theme of "CO2 concentration monitoring equipment," Fig. 5 (e)–(h) presents the knowledge structure and technological development trends. Fig. 5 (e) depicts the overall framework of the co-occurrence map for keywords related to "carbon dioxide concentration monitoring equipment," with "carbon dioxide", "gas sensors", and "air quality" at its core. Fig. 5 (f) further elucidates the crucial role of CO2 monitoring equipment in "air quality" management [24], particularly emphasizing significant advancements in "multiple sensor" applications such as photoacoustic sensors and fluorescent chemical sensors to enhance precision gas monitoring. Fig. 5 (g) focuses on "gas sensors" as an evolving branch, which shows that Advances in gas sensor technology support the precise monitoring of air quality [50], thus playing a key role in public health protection. Lastly, Fig. 5 (h) showcases the potential of monitoring devices for multi-pollutant joint detection, highlighting their value in environmental assessment by detecting gases like methane and ammonia simultaneously. In recent years, real-time integration and adaptability across various scenarios have emerged as a prominent research focus within air quality monitoring systems, indicating that improving sensor accuracy and environmental adaptability is a pivotal direction for future advancements [7].

Table 10
Top 20 high-frequency keywords in the CiteSpace of flue gas concentration monitoring equipment.

Number	Frequency	Centrality	keyword
1	32	0.83	carbon dioxide
2	12	0.20	gas sensors
3	10	0.12	air quality
4	9	0.17	co2
5	7	0.07	carbon dioxide sensor
6	6	0.09	gas sensor
7	6	0.03	temperature
8	6	0.07	air pollution
9	5	0.21	air quality monitoring
10	5	0.07	methane
11	5	0.04	adsorption
12	4	0.03	internet of things
13	4	0.05	sensor
14	4	0.05	emissions
15	4	0.05	ch4
16	4	0.02	co2 sensor
17	4	0.01	system
18	4	0.03	carbon monoxide
19	3	0.02	chemical sensors
20	3	0.15	capture

5.2. The hardware-based concentration monitoring technologies

By using different measurement principles and methods, concentration monitoring equipment can accurately, quickly, and stably measure various pollutants in the flue gas, such as sulfur dioxide, nitrogen oxides, carbon monoxide, oxygen, chlorine, and fluorine. Concentration monitoring equipment can effectively monitor flue gas concentration and transmit data in real-time to the CEMS system. Gas analyzers designed for concentration monitoring serve as essential components within CEMS. These analyzers facilitate the continuous, real-time monitoring and analysis of diverse pollutant concentrations present in flue gases. The methodologies employed in gas analyzers commonly encompass optical absorption, optical emission, mass spectrometry, chemiluminescence, and other relevant techniques. A comparative assessment of the merits and limitations of these monitoring methods is provided in Table 11 for further reference and elucidation.

Quantitative analysis of CO2 could be conducted by using various colorimetric and luminescent optical sensors. The optical sensors are sensitive to variations in humidity and osmotic pressure [78]. The infrared absorption spectroscopy for CO2 monitoring in agricultural settings utilized a multi-channel gas chamber and dual-channel detection method. This approach enabled precise monitoring of GHGs, simultaneously enhancing light collection efficiency while mitigating the impact of environmental factors. The on-site experiments at the Shelin Town farm in Jilin Province, evaluating the monitoring performance of the infrared absorption spectroscopy sensor for CO2 concentration. Within the measurement range of 30–5000 ppm, the relative detection error was less than 5 %. Furthermore, the fluctuations in long-term (10-h) stability measurements for 500 ppm CO2 and 2000 ppm CO2 samples were 1.08 % and 3.6 %, respectively, demonstrating the method's excellent stability. This study underscores the potential of infrared absorption spectroscopy technology to meet diverse requirements, including a wide measurement range, rapid response, and high sensitivity [79].

Besides, ultraviolet (UV) laser absorption of CO2 could determine environmental temperature. Eamonn Hawe et al. [92] utilized continuous-wave laser radiation at 244 and 266 nm to detect the spectrally smooth UV absorption of CO2. Compared with the entropy assumption structure, the experimental results of UV absorption showing outstanding consistency. The tunable laser absorption

Table 11
Comparison of concentration monitoring technologies.

Technology	Advantages	Disadvantages
Optical absorption monitoring technology [78,79].	High accuracy, capable of online continuous monitoring, high selectivity, applicable for monitoring different types of gases.	Significantly affected by smoke particles and humidity in the flue gas, high requirements for optical path, high cost.
Optical emission monitoring technology [80]	Non-contact measurement, no need for sampling or sample treatment, can simultaneously monitor multiple pollutants, fast measurement speed, and no need for gas calibration.	Affected by particulate matter and humidity in the flue gas, limited to measuring fluorescent pollutants, and high equipment cost.
Mass spectrometry monitoring technology [81]	High sensitivity, high selectivity, high accuracy, high resolution	Complex maintenance and operation, slow analysis speed, and complex sample pretreatment required.
Chemiluminescence monitoring technology [80,82].	High sensitivity, strong selectivity, real-time capability, and wide applicability.	The monitoring error is relatively large, it has higher cost, and standardization and calibration present significant challenges.
Laser Absorption Spectroscopy Monitoring Technology [83]	Fast measurement, high accuracy, no need for separation, unaffected by other interfering factors.	Requires substantial equipment and technical support, exhibits strong selectivity towards gases, necessitates stable laser sources and detectors, and incurs high maintenance costs.
Electrochemical sensor monitoring technology [82, 84].	Sensitive response, low cost, and other advantages.	The sensor has high requirements for environmental conditions such as temperature and humidity, and it has certain limitations in terms of response and selectivity to different chemical substances.
Fiber optic sensor monitoring technology [85–87]	Fast measurement, high accuracy, unaffected by other interfering factors	Expensive equipment, difficult to maintain
Absorption spectroscopy monitoring technology [79]	High precision, high sensitivity, and no need for calibration	Susceptible to interference from impurities in the flue gas, requires pre-treatment of the flue gas, and takes longer to achieve stable and accurate measurements.
Fluorescence spectroscopy monitoring technology [78].	Higher selectivity and sensitivity, less affected by impurities in the flue gas.	Requires pre-treatment of flue gas to avoid interference from other substances on the fluorescence signal, and special spectrometers and detection systems are needed, resulting in high costs.
Microwave gas measurement and monitoring technology [88, 89]	Fast measurement speed, high accuracy, short response time, high sensitivity to changes in gas composition, and long lifespan. It is suitable for online and real-time measurements, making it applicable in a wide range of industries and settings. It can operate in harsh environments characterized by high temperatures and pressures.	Requires certain requirements for the dielectric constant of the gas being measured. It involves a high level of complexity and is susceptible to interference from factors such as gas composition, temperature, and pressure
Infrared measurement and monitoring technology [76, 90,91].	High measurement accuracy, fast response speed, wide applicability, no need for sample processing, non-destructive sampling and chemical treatment of the measured gas, capable of online real-time monitoring, high flexibility and versatility.	Requires certain molecular structure and chemical bonding of the measured gas. May have measurement errors for gases with weak chemical bonds or complex molecular structures. Susceptible to saturation effects of infrared absorption, leading to distorted monitoring results. Requires high technical expertise and maintenance costs. High cost involved.

spectroscopy is commonly applied for an underwater CO2 concentration monitoring system, successfully implemented in the South China Sea to monitor subsea CO2 gas. Leveraging the high precision and rapid response of laser absorption, they designed a simple sensor structure to achieve fast non-invasive gas analysis. The monitoring achieved high precision with an average response time of 0.4 s, reaching 0.72 parts per billion by volume (PPBV) [83]. Laser absorption spectroscopy effectively addresses difficulties encountered in underwater sensing, including high pressure, frequent vibrations, and limited accessibility during malfunctions.

Huan Wang et al. [80] have developed an optical launched method with plasmonic enhancement, which shows a good performance in real-time low-concentration CO2 monitoring. Experimental results confirm its suitability for quantitatively detecting CO2 concentrations in gas mixtures ranging from 0.4 % to 5 %, with detection limits as low as 0.031 %. Therefore, optical launched method exhibits high sensitivity, strong CO2 recognition capabilities, and outstanding robustness. David Smith et al. [81] researched mass spectrometry monitoring technology to measure the concentration of CO2 in moist air. This technique exhibits high sensitivity, enabling precise quantification of CO2 levels in humid air. Additionally, it was observed that the sensitivity and accuracy of CO2 monitoring increase as the gas flow rate decreases.

Optical absorption and emission methods are relatively sensitive to factors such as particulate matter and humidity in flue gas, while mass spectrometry requires more complex operation and maintenance. Compared to other traditional concentration monitoring methods, laser absorption spectroscopy offers advantages such as rapid measurement, high precision, no need for separation, and immunity to interference from other factors. When selecting and using gas analyzers, comprehensive consideration and optimization should be carried out based on specific monitoring requirements and practical circumstances. Electrochemical sensor method is a concentration monitoring method based on oxidation-reduction reactions [93].

Kamalakanta Behera et al. [82] summarized the applications of optical and electrochemical CO2 sensors. They emphasize that maintaining extremely dry conditions or minimizing the presence of water molecules is essential when using this technology for environmental monitoring. The influence of temperature significantly impacts the viscosity of the medium, further affecting the monitoring accuracy. Schwandt et al. [84] innovated a solid-state electrochemical gas sensor. The sensor detects CO2 in inert gases, which exhibits high precision and rapid response characteristics. Within the temperature range of 300–600 °C, the designed sensor generates voltages consistent with thermodynamic expectations, and the deviation is less than 1 mV. For a long-term usage, this sensor maintains excellent functionality and drift-free performance during continuous. The electrochemical sensor method offers advantages such as fast measurement, sensitive response, and low cost. However, this sensor requires high environmental temperature, humidity, and other conditions, and it has certain limitations in terms of response and selectivity to different chemical substances.

Infrared fiber optic sensors could monitor the CO2 emissions from diesel engines, which is suitable for harsh engine exhaust environments. Meanwhile, infrared fiber optic sensors have low cost and high accurate CO2 measurement. The applications of infrared fiber optic sensors are non-cross-sensitive to other pollutants, water vapor, smoke, or particulate matter [85]. Cheng-Shane et al. [86] provide an overview of the research progress in fluorescence oxygen and CO2 optical fiber sensors. They emphasize that optical fiber CO2 sensors based on a sol-gel matrix is more sensitive. Furthermore, they introduce a modified Stern-Volmer model to compensate for temperature drift in oxygen concentration measurements.

Eamonn Hawe et al. [87] investigated an optical fiber sensor for detecting NOx (NO2 and NO) and CO2 in road vehicle exhaust systems. The experiment demonstrated that the sensor can achieve concentration measurements at the parts per million (ppm) level and exhibits excellent monitoring stability. Compared to other traditional concentration monitoring methods, fiber optic sensor method offers advantages such as fast measurement, high accuracy, immunity to other interfering factors, good reliability, long-distance transmission capability, and ease of online monitoring. However, due to the current stage of development, the equipment prices for this technology are relatively high.

Microwave gas measurement technology allows for online and real-time measurements, making it suitable for harsh environments [88,89] such as, high temperature and high pressure, and it has a wide range of applications. However, there are limitations to microwave gas measurement technology. It requires a certain dielectric constant of the measured gas, and specific research and design are needed for measuring different gases. Additionally, microwave signals can be easily affected by factors such as gas composition, temperature, and pressure during propagation in the gas, making the technology reliant on complex instruments and equipment, resulting in higher costs.

Infrared measurement technology is commonly used for monitoring gas concentrations [76,90,91]. It offers high measurement accuracy, fast response speed, wide applicability, and does not require sample handling. This technology enables online real-time monitoring without destructive gas sampling or chemical treatment. The concentration monitoring sensor based on infrared absorption spectroscopy exhibits outstanding monitoring sensitivity [94]. The sensor’s performance could be improved through noise reduction, optical path optimization, and balanced radiation detection [94].

Over 90 % of thermal power plants in China have installed CEMS for online monitoring of pollutants and particulate matter [60]. However, the integration of carbon dioxide concentration monitoring modules into CEMS is still relatively limited. Wang Mihan, Zhu Lin, and others [11]integrated a carbon dioxide monitoring module based on dilution sampling method into an existing CEMS at a thermal power plant in China to monitor its carbon emissions. The results showed that the carbon emissions measured by CEMS were lower than the estimates obtained using emission factor method, with an error fluctuating between 17 % and 20 %.

Achieving high accuracy remains a challenge, especially measuring low concentrations of certain gases, such as CO2. Calibration and quality control mechanisms are crucial to address this issue. The monitoring technologies may exhibit cross-sensitivity, where interference from other gases affects the accuracy. This is particularly relevant in complex industrial settings with multiple gas emissions. Meanwhile, rapid response times are demand for dynamic monitoring and smart control of emissions. Most of the concentration monitoring technologies discussed above are struggle to provide real-time data, impacting their effectiveness in dynamic operational environments. Industrial environments often involve harsh conditions such as high temperatures, high particulate matter, and corrosive substances. Ensuring the robustness and durability under such conditions is important. Moreover, high initial and maintenance costs associated with sophisticated monitoring processes maybe a barrier to widespread adoption, particularly for smaller facilities or in developing economies.

6. Conclusion

In an era of increasing constraints on global carbon capacity, the unchecked growth of carbon emissions has imposed significant social and environmental costs. Within complex industrial settings—characterized by intricate production processes, diverse energy sources, and often incomplete records—obtaining accurate, short-term carbon emission factors has become essential for reliable carbon accounting. However, the dynamic and context-specific nature of emissions poses substantial challenges to the broad adoption and standardization of carbon accounting methods across industries. The use of real-time, context-specific emission factors is critical in overcoming these obstacles, enhancing the precision and applicability of carbon accounting methodologies, and enabling their effective implementation across varied industrial landscapes.

Carbon monitoring technology, particularly gas detection-based systems, provides a promising approach to address common issues in carbon accounting, such as data inaccuracy, incompleteness, and lack of timeliness. By offering real-time data collection, these technologies can complement traditional accounting approaches. However, widespread adoption of carbon monitoring is currently limited by the high costs associated with stationary emission monitoring and the technical complexity of tracking non-stationary emissions. Policy support is essential to overcome these barriers, with incentives and regulatory standards playing a crucial role in reducing costs and encouraging innovation. Policies focused on promoting cost-effective and adaptable monitoring technologies can help accelerate the integration of real-time monitoring with carbon accounting, ultimately supporting effective emissions management and advancing carbon reduction targets on a broader scale.

As carbon monitoring technology continues to evolve to meet the complex demands of industrial carbon management, the integration of CEMS with carbon accounting represents a promising solution to improve data accuracy, timeliness, and adaptability across various industrial applications. CEMS, powered by advancements in CO_2 concentration monitoring, such as high-sensitivity NDIR and nanotechnology-enabled sensors, enhances the precision of carbon data collection by providing reliable and adaptable emission factors that account for the dynamic nature of industrial emissions. Additionally, integrating artificial intelligence and data analytics within CEMS facilitates sophisticated data interpretation and predictive insights, making it suitable for diverse emissions sources. While challenges remain—particularly the high costs of implementing CEMS for stationary sources and technical difficulties in non-stationary emissions monitoring—future research should focus on reducing system costs, promoting wireless and intelligent system deployments, and improving sustainability. These advancements will position CEMS as a pivotal technology in the carbon management ecosystem, enabling accurate, actionable data to guide emissions reduction strategies and support emerging carbon market mechanisms, ultimately contributing to a more effective and efficient carbon reduction infrastructure.

CRediT authorship contribution statement

Ning Ding: Writing – review & editing, Validation, Supervision, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Yanheng Xi:** Writing – original draft, Visualization, Validation, Software, Resources, Methodology, Investigation, Data curation. **Wenting Jiang:** Validation, Software, Resources, Methodology, Investigation. **Hongwei Li:** Supervision, Project administration, Funding acquisition. **Jun Su:** Supervision, Project administration, Funding acquisition. **Sixiang Yang:** Resources, Project administration, Funding acquisition. **Tek Tjing Lie:** Writing – review & editing, Validation, Supervision.

Data availability statement

The data that has been used is confidential/Data available within the article or its supplementary materials.

The authors confirm that the data supporting the findings of this study are available within the article [and/or] its supplementary materials.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:Ning Ding reports financial support was provided by Southwest Petroleum University. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix

Table 1
List of Citespace Research on CEMS Technology Based on Bibliometric Analysis

Title	Author(s) year	Key words	Sources	Research field
Technical Study on Flue gas Continuous Emission Monitoring Systems For Power plant	Zheng, HM et al., 2014 [56]	Continuous Emission Monitoring System (CEMS); Flue Gas; Power Plant; Dust monitoring; In-situ Analyzer	ADVANCES IN MECHATRONICS, AUTOMATION AND APPLIED INFORMATION	Automation & Control Systems; Engineering, Mechanical; Materials
Benefits of current and future policies on emissions of China's coal-fired power sector indicated by continuous emission monitoring	Zhang, Y et al., 2019 [57]	Coal-fired power plant; CEMS; Ultra-low emission policy; Emission control	ENVIRONMENTAL POLLUTION	Environmental Sciences
Uncertainty analysis of stack gas flow measurements with an S-type Pitot tube for estimating greenhouse gas emissions using a continuous emission	Kang, W et al., 2020 [60]	greenhouse gas emissions; continuous emission monitoring system; volumetric gas flowrate measurement; uncertainty; S-type Pitot tube	METROLOGIA	Instruments & Instrumentation; Physics, Applied
Deposition Loss of Particles in the Sampling Lines of continuous Emission Monitoring System (CEMS) in Coal-fired Power Plants	Zhu, RR et al., 2018	Deposition; CEMS; Sampling; Coal-fired power plant	AEROSOL AND AIR QUALITY RESEARCH	Environmental Sciences
An improved hourly-resolved NOx emission inventory for power plants based on continuous emission monitoring system (CEMS) database: A case in Jiangsu, China	X. Gu I et al., 2022 [58]	ANFIS; Continuous emission monitoring system; Model prediction; Incineration; Clinical waste; CO emission	Journal of Cleaner Production	Computer Science, Artificial Intelligence
Estimating carbon dioxide emissions from electricity generation in the United States: How sectoral allocation may shift as the grid modernizes	A. L. Eberle et al., 2020 [59,69]	Sintered flue gas emissions; China; Continuous emission monitoring system; Emissions standard-reaching rate; Oxygen content	Energy Policy	Green & Sustainable Science & Technology; Engineering, Environmental;
Microfluidic Airborne Metal Particle Sensor Using Oil Microcirculation for Real-Time and Continuous Monitoring of Metal Particle Emission	Yoon, JS et al., 2021	microfluidics; microcirculation; particle-to-liquid collection; airborne metal particle; continuous and real-time monitoring; capacitive	MICROMACHINES	Chemistry, Analytical; Nanoscience & Nanotechnology; Instruments &
The valuation relevance of greenhouse gas emissions under the European Union carbon emissions trading scheme	P. M. Clarkson et al., 2006	NOx emission; Boilers; CFD simulation; Inferential sensor; Neural networks; Combustion	European Accounting Review,	Automation & Control Systems; Engineering, Electrical & Electronic
SOFT SENOR PREDICTIVE STUDY ON SO2 EMISSION FROM THERMAL POWER PLANT	Zheng, HM et al., 2016	Continuous Emission Monitoring System (CEMS); soft sensing; RBF neural; network; BP neural network	ENERGY, ENVIRONMENTAL & SUSTAINABLE ECOSYSTEM DEVELOPMENT	Energy & Fuels; Environmental Sciences
Reliability analysis of continuous emission monitoring system with common cause failure based on fuzzy FMECA and Bayesian networks	Yang, YJ et al., 2022	CEMS; Fuzzy FMECA; Common cause failure (CCF); Bayesian network (BN); alpha-factor model	ANNALS OF OPERATIONS RESEARCH	Operations Research & Management Science
Development of a predictive emissions model using a gradient boosting machine learning method	Si, MX et al., 2020	Predictive emissions monitoring system; PEMS; XGBoost; Gradient boosting; NOxmonitoring	ENVIRONMENTAL TECHNOLOGY & INNOVATION	Biotechnology & Applied Microbiology; Engineering, Environmental;
Predicting CO and NOx emissions from gas turbines: novel data and a benchmark PEMS	Kaya, H et al., 2019	Predictive emission monitoring systems; CO; NOx; exhaust emission prediction; gas turbines; extreme learning machine; database	TURKISH JOURNAL OF ELECTRICAL ENGINEERING AND COMPUTER SCIENCES	Computer Science, Artificial Intelligence; Engineering, Electrical &
A VCSEL based system for on-site monitoring of low level methane emission	Kannath, A et al., 2011	Wavelength modulation spectroscopy; VCSEL; residual methane; tuneable diode lasers	VERTICAL-CAVITY SURFACE-EMITTING LASERS XV	Engineering, Electrical & Electronic; Optics; Physics, Applied
Air Quality Impact Assessment of a Waste-to-Energy Plant: Modelling Results vs. Monitored Data	Lonati, G et al., 2022	air quality; waste to energy; trace pollutants; measured emissions;	ATMOSPHERE	Environmental Sciences; Meteorology & Atmospheric Sciences

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Table 1 (*continued*)

Title	Author(s) year	Key words	Sources	Research field
		monitored data; atmospheric dispersion modelling		
The Effect of a Hybrid Pretreatment Device for CEMS on the Simultaneous Removal of PM2.5 and Water Vapor	Choi, IY et al., 2022	continuous emission monitoring system; hybrid cyclone; pretreatment device; PM2.5; cooling	ATMOSPHERE	Environmental Sciences; Meteorology & Atmospheric Sciences
A high temporal-spatial emission inventory and updated emission factors for coal-fired power plants in Shanghai, China	Chen, XJ et al.	DE Coal-fired power plants; Emission factor; CEMS; Unit-based	SCIENCE OF THE TOTAL ENVIRONMENT	Environmental Sciences
Feasibility of Using Isokinetic Sampling Techniques to Extract a Representative Sample from Processes in the United Kingdom	Nicklin, D et al., 2022	isokinetic sampling; gravimetric analysis; standard reference method; continuous emission monitoring system; particulate deposit; measurement	ATMOSPHERE	Environmental Sciences; Meteorology & Atmospheric Sciences
The impact of geometric parameters of a S-type Pitot tube on the flow velocity measurements for greenhouse gas emission monitoring	Nguyen, DT et al., 2019	Greenhouse gas emission; S-type Pitot tube; Yaw and pitch angle misalignment	FLOW MEASUREMENT AND INSTRUMENTATION	Engineering, Mechanical; Instruments & Instrumentation
Quantifying coal power plant responses to tighter SO2 emissions standards in China	Karplus, VJ et al. 2018	air pollution; satellite; high-frequency monitoring; China; policy	PROCEEDINGS OF THE NATIONAL ACADEMY OF SCIENCES OF THE UNITED STATES	Multidisciplinary Sciences
Development of A Low-Cost FPGA-Based Measurement System for Real-Time Processing of Acoustic Emission Data: Proof of Concept Using Control of carbon	Wirtz, SF et al., 2018	acoustic emission; structural health monitoring; real-time signal processing; FPGA; embedded linux; wavelet transform; pulsed laser	SENSORS	Chemistry, Analytical; Engineering, Electrical & Electronic; Instruments
The impact of carbon emissions trading on energy efficiency: Evidence from quasi-experiment in China's carbon emissions trading pilot	Q. Hong et al., 2022	UV; LED; sensing; analyzer; NOx; NO2; SO2; gas; absorption	Energy Economics	Nanoscience & Nanotechnology; Materials Science, Multidisciplinary;
Provision of primary NIST traceability to support vapor phase mercury emissions monitoring of combustion sources using isotope dilution	Long, SE et al. 2020	ercury emissions; Combustion sources; Coal; Electric utility; Inductively coupled plasma mass spectrometry; Isotope dilution mass	ATMOSPHERIC POLLUTION RESEARCH	Environmental Sciences
Air Pollutant Emission Abatement of the Fossil-Fuel Power Plants by Multiple Control Strategies in Taiwan	Tsai, JH et al., 2021	particulate matter (PM); sulfur oxide (SOx); nitrogen oxide (NOx); emission factor; fuel switch	ENERGIES	Energy & Fuels
Supervision and Fuzzy Control of a Manufacturing Process using LabVIEW	Zermane, H et al., 2017	Fuzzy control; manufacturing process; emission monitoring; bag filter;	2017 5 TH INTERNATIONAL CONFERENCE ON ELECTRICAL ENGINEERING - BOUMERDES	Engineering, Electrical & Electronic
Impact of Control Measures on Nitrogen Oxides, Sulfur Dioxide and Particulate Matter Emissions from Coal-Fired Power Plants in Anhui	Dai, HT et al., 2019	coal-fired power plants; CEMS; atmospheric pollutants; emission intensity; spatial and temporal variation	ATMOSPHERE	Environmental Sciences; Meteorology & Atmospheric Sciences
Developing a Cyber-Physical System for Promoting Green Engineering of Solid Waste Incineration	Lu, JW et al., 2019	Cyber-physical system; Smart city; Environmental information system; Waste incineration; NIMBY syndrome	PROCEEDINGS OF THE 2019 IEEE 16 TH INTERNATIONAL CONFERENCE ON	Automation & Control Systems; Computer Science, Hardware & Architecture;
Carbon dioxide emissions from the Geheyan Reservoir over the Qingjiang River Basin, China	Tan, DB et al., 2019	Reservoir; Carbon cycle; Carbon dioxide fluxes; Spatial and temporal variation	ECOHYDROLOGY & HYDROBIOLOGY	Ecology; Water Resources
Highlighting and overcoming data barriers: creating open data for retrospective analysis of US electric power systems by consolidating	Kasseris, E et al., 2018	power systems; EPA; data quality; operational behavior; open data; data merging	ENVIRONMENTAL RESEARCH COMMUNICATIONS	Environmental Sciences
Assessment of polychlorinated dibenzo-p-dioxin and dibenzofuran emissions from a	Rivera-Austrui et al., 2011	PCDD/Fs; Hazardous waste incineration; Long-term sampling; Congener profile; PCA	CHEMOSPHERE	Environmental Sciences

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Table 1 (*continued*)

Title	Author(s) year	Key words	Sources	Research field
hazardous waste incineration plant using long-term				
An inference model for combustion diagnostics in an experimental oil furnace	Fleury, AT et al., 2018	combustion diagnosis; furnace monitoring; image analysis; theDempster-Shafer method	EXPERT SYSTEMS	Computer Science, Artificial Intelligence; Computer Science, Theory
Production of nitrogen oxide gases from an oxic/anoxic process via nitrite: influence of liquid parameters and impact on mass balance	Eusebi, AL et al., 2015	nitrites; ORP; anaerobic digested supernatant; alternate biological process; nitrogen oxide	ENVIRONMENTAL TECHNOLOGY	Environmental Sciences
CEMS using Hot Wet Extractive Method Based on DOAS	Sun, B et al., 2011	hot wet extractive method; partial least squares un-linear regression; the on-line calibration; environmental monitoring	2011 INTERNATIONAL CONFERENCE ON OPTICAL INSTRUMENTS AND TECHNOLOGY:	Instruments & Instrumentation; Optics
On-line measurement of particle size and shape distributions of pneumatically conveyed particles through multi-wavelength based digital	Gao, LJ et al., 2012	Pulverized fuel; Particle size; Particle shape; Multi-wavelength lasers; RGB camera; Image processing	FLOW MEASUREMENT AND INSTRUMENTATION	Engineering, Mechanical; Instruments & Instrumentation
Continuous and high-precision atmospheric concentration measurements of COS, CO2, CO and H2O using a quantum cascade laser spectrometer (QCLS)	Kudo, H et al., 2013	Biosensor; gas sensor; NADH; formaldehyde; fiber-optic	IEEE SENSORS JOURNAL	Engineering, Electrical & Electronic; Instruments & Instrumentation;
Lab-scaled performance evaluation of novel water-lean solvents for post combustion CO2 capture	Tanthana, J et al. 2021	water-lean solvent; CO2 capture; CO2 absorption; lab-scale demonstration; amine emission	INTERNATIONAL JOURNAL OF GREENHOUSE GAS CONTROL	Green & Sustainable Science & Technology; Energy & Fuels; Engineering,
High temperature slagging gasification of municipal solid waste with biomass charcoal as a greener auxiliary fuel	Heberlein, S et al., 2022	High temperature slagging gasification plant; Greener auxiliary fuel; Biomass charcoal; Performance monitoring; Municipal solid waste	JOURNAL OF HAZARDOUS MATERIALS	Engineering, Environmental; Environmental Sciences
Environmental factors regulating winter CO2 flux in snow-covered black forest soil of Interior Alaska	Kim, Y et al., 2017	winter CO2 flux; ambient pressure; air temperature; snow depth; black spruce forest of Alaska	GEOCHEMICAL JOURNAL	Geochemistry & Geophysics
Edge effects on N2O, NO and CH4 fluxes in two temperate forests	Remy, E et al., 2017	Forest edge; Nitrogen deposition; Nitrous oxide; Nitric oxide; Methane	SCIENCE OF THE TOTAL ENVIRONMENT	Environmental Sciences
Domestic heat pumps in the UK: user behaviour, satisfaction and performance	Caird, S et al., 2012	Microgeneration heating and hot water systems; Domestic heat pumps;	ENERGY EFFICIENCY	Green & Sustainable Science & Technology; Energy & Fuels; Environmental
Asynchronous changes of CO2, H-2, and He concentrations in soil gases: A theoretical model and experimental results	Di Martino, RMR et al., 2016	soil gases; volcanic gas composition; volcano monitoring; hydrogen; carbon dioxide; helium	JOURNAL OF GEOPHYSICAL RESEARCH-SOLID EARTH	Geochemistry & Geophysics
Experimental research on selective adsorption of gaseous mercury (II) over SiO2, TiO2 and gamma-Al2O3	Zheng, YW et al. 2019	Hg-0 and HgCl2; Selective adsorption; gamma-Al2O3; Basic sites; SO2 interference	FUEL	Energy & Fuels; Engineering, Chemical
Assessing the levels of regulated metals in an urban area: A modelling and experimental approach	Lopes, D et al., 2022	Air pollution; Toxic elements; Lisbon; WRF-CAMx	ATMOSPHERIC ENVIRONMENT	Environmental Sciences; Meteorology & Atmospheric Sciences
An educated search for transiting habitable planets: (Research Note) Targetting M dwarfs with known transiting planets	Gillon, M et al., 2011	astrobiology; binaries: eclipsing; planetary systems; stars: individual:	ASTRONOMY & ASTROPHYSICS	Astronomy & Astrophysics
Carbon dioxide spatial variability and dynamics for contrasting land uses in central Brazil agricultural frontier from remote sensing data	Rossi, FS et al., 2022	Environmental degradation; Emission; Climate change; Orbital sensor	JOURNAL OF SOUTH AMERICAN EARTH SCIENCES	Geosciences, Multidisciplinary
Efficient Detection of Environmental Violators: A Big Data Approach	Chang, XY et al., 2021	big data analytics; positive and unlabeled learning; sustainability; violator detection	PRODUCTION AND OPERATIONS MANAGEMENT	Engineering, Manufacturing; Operations Research & Management Science

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Title	Author(s) year	Key words	Sources	Research field
Pulverized coal flow metering on a full-scale power plant using electrostatic sensor arrays	Qian, XC et al., 2014	Pulverized coal; Gas solid two-phase flow; Particle velocity; Mass flow rate; Fuel distribution; Electrostatic sensor; Cross-correlation	FLOW MEASUREMENT AND INSTRUMENTATION	Engineering, Mechanical; Instruments & Instrumentation
K-CM application for supervised pattern recognition at Mt. Etna: an innovative tool to forecast flank eruptive activity	Brancato, A et al., 2019	Mt.Etna volcano; Flank eruption; Monitoring data complex system; Neural networks; Supervised pattern recognition	BULLETIN OF VOLCANOLOGY	Geosciences, Multidisciplinary
On the thermal and visual pedestrians' perception about cool natural stones for urban paving: A field survey in summer conditions	Rosso, F et al., 2016	Outdoor thermal comfort; Outdoor visual comfort; Cool pavement; Passive cooling system; Urban heat island; Mitigation and adaptation	BUILDING AND ENVIRONMENT	Construction & Building Technology; Engineering, Environmental;
changes of global power generation capacity towards sustainability and the risk of stranded investments supported by a sustainability indicator	Farfan et al., J2017	Power generation mix; Power system evolution; Sustainability indicator; Technical lifetime; Stranded assets	JOURNAL OF CLEANER PRODUCTION	Green & Sustainable Science & Technology; Engineering, Environmental;
An on-line infrared spectroscopic system with a modified multipath White cell for direct measurements of N2O from NH3-SCR reaction	Kim, DW et al., 2010	Long Path White Cell; On-line N2O Measurements; Commercial V2O5-WO3/TiO2 Catalysts; NH3-SCR Reaction; N2O Formation	KOREAN JOURNAL OF CHEMICAL ENGINEERING	Chemistry, Multidisciplinary; Engineering, Chemical
Shipboard observations of atmospheric oxygen in the Southern Ocean	Morimoto, S et al., 2021	Atmospheric oxygen; O-2/N-2; Southern ocean; JARE	POLAR SCIENCE	Ecology; Geosciences, Multidisciplinary
Reduction of HgCl(2)to Hg-0 in flue gas at high temperature. Part I: Influences of oxidative species	Huang, TF et al., 2022	Hg-CEMS; High-temperature decomposition; HgCl (2) (g) reduction; Hg (0) (g) re-oxidation; Oxidative species	FUEL	Energy & Fuels; Engineering, Chemical
Comparison and validation of band residual difference algorithm and principal component analysis algorithm for retrievals of atmospheric SO2	Yan, HH et al., 2016	trace gas SO2; satellite remote sensing; comparison and validation; uncentainty analysis	ACTA PHYSICA SINICA	Physics, Multidisciplinary

Table 2
Citespace literature analysis research list of flue gas concentration monitoring technology

Title	Author(s) year	Key words	Sources	Research field
Carbon dioxide gas sensor using a graphene sheet	Yoon, HJ et al., 2011	Graphene; Mechanical cleavage; Gas sensor; Carbon dioxide sensor	SENSORS AND ACTUATORS B-CHEMICAL	Chemistry, Analytical; Electrochemistry; Instruments & Instrumentation
Monitoring and Analysis of Outdoor Carbon Dioxide Concentration by Autonomous Sensors	Soares, PH et al., 2022	data mining; air quality monitoring; sensors; carbon dioxide; pollution	ATMOSPHERE	Environmental Sciences; Meteorology & Atmospheric Sciences
Technical Study on Flue gas Continuous Emission Monitoring Systems For Power plant	H. M. Zheng et al., 2012 [56]	Carbon dioxide; long period grating; absorption; chemical sensors	INTERNATIONAL CONFERENCE ON SYSTEM OF SYSTEMS ENGINEERING (SOSE)	Remote Sensing; Optics
Experimental assessment of an indirect method to measure the post-combustion flue gas flow rate in waste-to-energy plant based on multi-point measurements	G. Bellani et al., 2023	Carbon dioxide sensor; Gas sensor; Ionic liquids; Optical sensor; Smart packaging; Food spoilage	Waste Manag	Chemistry, Analytical; Electrochemistry; Instruments & Instrumentation
A novel technical route based on wet flue gas desulfurization process for flue gas dehumidification, water and heat recovery	Z. Chen et al., 2020	Conducting polymer; Polyaniline; Poly(ethyleneimine); Gas sensor; Carbon	Applied Thermal Engineering	Chemistry, Analytical
Solid State Electronic Sensors for Detection of Carbon Dioxide	Hannon, A et al., 2019	carbon dioxide sensor; CO2 sensor; gas sensor; room temperature gas sensing; functionalized	SENSORS	Chemistry, Analytical; Engineering, Electrical & Electronic; Instruments

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Table 2 (*continued*)

Title	Author(s) year	Key words	Sources	Research field
		nanotubes; electronic nose; smartphone sensor;		
Analysis of Carbon Dioxide Concentration Prediction Model and Diffusion Tendency of Expiratory by Simultaneous Multipoint Sensing	Moritani et al., M2020	carbon dioxide concentration sensor; simultaneous multipoint sensing; indoor air quality; indoor measurement	APPLIED SCIENCES-BASEL	Chemistry, Multidisciplinary; Engineering, Multidisciplinary; Materials
Effects of natural gas composition on performance and regulated, greenhouse gas and particulate emissions in spark-ignition engines	R. Amirante et al., 2017	Infrared; Absorption; Spark plug sensor; Carbon dioxide; Gaseous water;	Energy Conversion and Management	Optics; Spectroscopy
Development & Characterization of NDIR based CO2 Sensor for Manned Space missions	D. S. Shah et al., 2016	Optical sensor; Fluorescence; Carbon dioxide sensor; Ratiometric measurements; Sol-gel	TECHNIQUES AND APPLICATIONS	Biochemical Research Methods; Chemistry, Analytical
Calibration method for carbon dioxide sensors to investigate direct methanol fuel cell efficiency	Staehler, M et al., 2014	Direct methanol fuel cell; Crossover; Carbon dioxide sensor; Calibration technique; Error analysis; Carbon dioxide diffusion	JOURNAL OF POWER SOURCES	Chemistry, Physical; Electrochemistry; Energy & Fuels; Materials
Analysis of Carbon Dioxide Concentration in a Room of Multiple Persons by Simultaneous Multi-Point Sensing	Watanabe, N et al., 2020	Ambient Intelligence; Carbon Dioxide Concentration; Indoor Measurement; Simultaneous Multi-points Sensing	2020 IEEE INTERNATIONAL CONFERENCE ON SYSTEMS, MAN, AND CYBERNETICS	Computer Science, Cybernetics; Computer Science, Information Systems
Real-Time Indoor Carbon Dioxide Monitoring Through Cognitive Wireless Sensor Networks	Spachos, P et al., 2016	Wireless sensor networks; indoor air quality monitoring; real-time monitoring; carbon dioxide monitoring	IEEE SENSORS JOURNAL	Engineering, Electrical & Electronic; Instruments & Instrumentation;
Bayesian filtering for building occupancy estimation from carbon dioxide concentration	Jiang, CY et al., 2020	Building occupancy estimation; Carbon dioxide concentration; Bayesian filtering; Inhomogeneous Markov model; Ensemble extreme learning machine	ENERGY AND BUILDINGS	Construction & Building Technology; Energy & Fuels; Engineering, Civil
The microprocessor device for measurement of concentration of carbon dioxide in the environment	Grychowski, T et al., 2012	gas measurements; measuring device; carbon dioxide; ventilation parameters; infrared absorption sensor	PRZEGLAD ELEKTROTECHNICZNY	Engineering, Electrical & Electronic
Direct visualization of carbon dioxide field flooding: Optical and concentration level comparison of diffusor effectiveness	Vandenberghe, S et al., 2020	carbon dioxide; field-flooding; air emboli; prevention; neuroprotection	JOURNAL OF THORACIC AND CARDIOVASCULAR SURGERY	Cardiac & Cardiovascular Systems; Respiratory System; Surgery
Technical Study on Flue gas Continuous Emission Monitoring Systems For Power plant	H. M. Zheng et al., 2012 [56]	NASICON; Carbon dioxide; Gas sensor; Excimer laser; Solid electrolyte; Grain size; Laser annealing; Scanning electron microscopy	INTERNATIONAL CONFERENCE ON SYSTEM OF SYSTEMS ENGINEERING	Materials Science, Multidisciplinary; Materials Science, Coatings
Speciation in Application Environments for Dissolved Carbon Dioxide Sensors	Bhatia, S et al., 2015	Dissolved inorganic carbon; Dissolved CO2; Hydrochemistry; Fiber-optic dissolved gas sensing; phreeqc	WATER AIR AND SOIL POLLUTION	Environmental Sciences; Meteorology & Atmospheric Sciences; Water
Analysis of the Trends Between Indoor Carbon Dioxide Concentration and Plug-Level Electricity Usage Through Topological Data Analysis	Endo, S et al., 2022	Sensors; Visualization; multidimensional time-series data; topological data analysis; mapper; indoor carbon dioxide concentration; energy	IEEE SENSORS JOURNAL	Engineering, Electrical & Electronic; Instruments & Instrumentation;
Detection of Carbon Dioxide Concentration in Soil Profile Based on Nondispersive Infrared Spectroscopy Technique	Tu, ZH et al., 2015	Nondispersive infrared spectroscopy technique; Soil profile; Carbon dioxide; Carbon flux	SPECTROSCOPY AND SPECTRAL ANALYSIS	Spectroscopy
The measurement of dissolved and gaseous carbon dioxide concentration	Zosel, J et al., 2011	CO2 sensor; Severinghaus electrode; solid electrolyte sensor; IR; NDIR; sensor application	MEASUREMENT SCIENCE AND TECHNOLOGY	Engineering, Multidisciplinary; Instruments & Instrumentation

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Table 2 (*continued*)

Title	Author(s) year	Key words	Sources	Research field
Fast initializing solid state electrochemical carbon dioxide sensor fabricated by a tape casting technique using yttria stabilized zirconia	Han, HJ et al., 2017	Carbon dioxide sensor; Bi-electrolyte; Tape casting; Yttria stabilized zirconia; Sodium beta alumina	SENSORS AND ACTUATORS B-CHEMICAL	Chemistry, Analytical; Electrochemistry; Instruments & Instrumentation
Wireless Kitchen Fire Prevention System Using Electrochemical Carbon Dioxide Gas Sensor for Smart Home	Kweon, SJ et al., 2022	carbon dioxide sensor; fire alarm; fire safety; gas stove; moving average; on-off keying; wireless communication	SENSORS	Chemistry, Analytical; Engineering, Electrical & Electronic; Instruments
Research of Fiber Carbon Dioxide Sensing System Based Laser Absorption Spectrum	Wei, YB et al., 2012	Carbon Dioxide; fiber sensor; laser absorption spectrum; distributed feedback laser; gas cell; gob Fire	THIRD ASIA PACIFIC OPTICAL SENSORS CONFERENCE	Engineering, Electrical & Electronic; Optics; Physics, Applied
A Sensitive Carbon Dioxide Sensor Based on Photoacoustic Spectroscopy with a Fixed Wavelength Quantum Cascade Laser	Qiao, SD et al., 2019	photoacoustic spectroscopy; carbon dioxide detection; quantum cascade	SENSORS	Chemistry, Analytical; Engineering, Electrical & Electronic; Instruments
Monitoring of hourly carbon dioxide concentration under different land use types in arid ecosystem	Turk, KGB et al., 2022	air pollution; carbon dioxide; land use; land cover	OPEN LIFE SCIENCES	Biology
Microfluidic optoelectronic sensor based on a composite halochromic material for dissolved carbon dioxide detection	Zilberman, Y et al., 2014	Halochromic dye; Ion pair; Optoelectronic sensor; Microfluidics; Carbon dioxide	SENSORS AND ACTUATORS B-CHEMICAL	Chemistry, Analytical; Electrochemistry; Instruments & Instrumentation
Multi-parameter monitoring of binary gas mixtures: Concentration and flow rate by DC excitation of thermal sensor arrays	Hepp, CJ et al., 2017	Flow sensor; Thermal sensor; Time independent excitation; Thermal conductivity; Gas concentration; Flow rate	SENSORS AND ACTUATORS A-PHYSICAL	Engineering, Electrical & Electronic; Instruments & Instrumentation
Dual core photonic crystal fiber based carbon dioxide gas sensor	Sharma, S et al., 2022	photonic crystal fiber; CO2 sensor; length; refractive index unit; transmission signal	2022 WORKSHOP ON RECENT ADVANCES IN PHOTONICS (WRAP)	Engineering, Electrical & Electronic; Optics
Research on a Prediction Method for Carbon Dioxide Concentration Based on an Optimized LSTM Network of Spatio-Temporal Data Fusion	Meng, J et al., 2022	carbon emissions; wireless carbon sensor network; optimized LSTM network; multi-source data fusion	IEICE TRANSACTIONS ON INFORMATION AND SYSTEMS	Computer Science, Information Systems; Computer Science, Software
Low cost, mobile sensor system for measurement of carbon dioxide in permafrost areas	Eberhardt, A et al., 2014	permafrost; low cost; mid infrared; carbon dioxide; optical; III-V semiconductor; MIR-LED; photoconductor; photometer	28 TH EUROPEAN CONFERENCE ON SOLID-STATE TRANSDUCERS (EUROSENSORS 2014)	Nanoscience & Nanotechnology; Remote Sensing
A novel graphene-based electroluminescent gas sensor for carbon dioxide detection	Seekaew, Y et al., 2019	AC-EL; Gas sensor; CO2 detection; Electroluminescent sensor; Graphene	APPLIED SURFACE SCIENCE	Chemistry, Physical; Materials Science, Coatings & Films; Physics,
Monitoring Technology for Gamma-Aminobutyric acid Production in Polished Mochi Barley Grains using a Carbon Dioxide Sensor	Watanabe, Y et al. 2015	arbon dioxide (CO2); CO2 sensor; glutamate decarboxylase; gamma-aminobutyric acid (GABA); mochi barley	JOURNAL OF FOOD SCIENCE	Food Science & Technology
A fast calibration algorithm for Non-Dispersive Infrared single channel carbon dioxide sensor based on deep learning	Mao, KJ et al., 2021	CO2; Single-channel sensor; Non-Dispersive Infrared (NDIR); Fast calibration; Deep learning	COMPUTER COMMUNICATIONS	Computer Science, Information Systems; Engineering, Electrical
Carbon dioxide sensing characteristics of ZnO nanorods	Adithyaraj, KS et al., 2021	Chemi-resistive sensor; ZnO nanorod; CO2 sensing	MATERIALS TODAY-PROCEEDINGS	Materials Science, Multidisciplinary
Experimentally validated CFD analysis on sampling region determination of average indoor carbon dioxide concentration in occupied space	Bulinska, A et al., 2014	Metabolic carbon dioxide; Pollution spatial distribution; Representative	BUILDING AND ENVIRONMENT	Construction & Building Technology; Engineering, Environmental;

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Table 2 (*continued*)

Title	Author(s) year	Key words	Sources	Research field
Surface acoustic wave sensor based on Au/TiO2/PEDOT with dual response to carbon dioxide and humidity	Wang, CC et al., 2022	Surface acoustic wave; Gas sensor; Humidity; Carbon dioxide; Double	ANALYTICA CHIMICA ACTA	Chemistry, Analytical
A PCB based chemiresistive carbon dioxide sensor operating at room temperature under different relative humidity	Bag, S et al., 2018	functionalized MWCNTs; polymer composites; chemiresistive sensor; CO2 gas sensing	2018 IEEE 13 TH NANOTECHNOLOGY MATERIALS AND DEVICES CONFERENCE (NMDC)	Engineering, Electrical & Electronic; Nanoscience & Nanotechnology;
Interfacial impedance based electrochemical detection of carbon dioxide using RTIL	Munje, RD et al., 2016	Room temperature ionic liquids; carbon dioxide detection; electrochemical sensor	2016 IEEE NANOTECHNOLOGY MATERIALS AND DEVICES CONFERENCE (NMDC)	Engineering, Electrical & Electronic; Nanoscience & Nanotechnology;
Room-temperature operated cyano-terminated ethynylated-thiourea as a resistive-type carbon dioxide (CO2) gas sensor	Daud, AI et al. 2019	Ethynylated-thiourea; Resistive-type sensor; Room temperature sensor;	ORGANIC ELECTRONICS	Materials Science, Multidisciplinary; Physics, Applied
Method to determine the suitability of non-dispersive infrared carbon dioxide sensor models in Heating, Ventilation and Air Conditioning	Nutsch, S et al., 2021	CO2 sensor; HVAC system; demand controlled ventilation; power measurement; non-dispersive infrared sensor	2021 IEEE SENSORS APPLICATIONS SYMPOSIUM (SAS 2021)	Engineering, Electrical & Electronic; Instruments & Instrumentation
A Method to Calibrate the Carbon Dioxide (Chemical) Stimuli of Pneumatic Esthesiometer Externally	Jayakumar, V et al., 2019	pneumatic esthesiometer; calibration; psychophysics; corneal sensitivity; carbon dioxide	TRANSLATIONAL VISION SCIENCE & TECHNOLOGY	Ophthalmology
Potentiometric carbon dioxide sensor based on thin Li3PO4 electrolyte and Li2CO3 sensing electrode	Lee, I et al., 2014	CO2 gas sensor; Lithium phosphate; Lithium carbonate; Thin solid electrolyte	IONICS	Chemistry, Physical; Electrochemistry; Physics, Condensed Matter
The influence of CO2 gas sensor parameters on its operation characteristic	Wysokinski, K et al., 2015	Etched fibers; optical fiber sensors; silica gel sensors; carbon dioxide sensors; sol-gel technique	OPTICAL FIBERS AND THEIR APPLICATIONS 2015	Optics; Physics, Applied
A Dual-Band Carbon Dioxide Sensor Based on Metal-TiO2-Metal Metasurface Covered by Functional Material	Long, W et al. 2022	metasurface; metal-insulator-metal; PHMB; carbon dioxide	PHOTONICS	Optics
Performance Evaluation of Spaceborne Integrated Path Differential Absorption Lidar for Carbon Dioxide Detection at 1572 nm	Wang, SB et al., 2020	carbon dioxide; IPDA lidar; error analysis; pseudo data simulation	REMOTE SENSING	Environmental Sciences; Geosciences, Multidisciplinary; Remote Sensing;
Simultaneous detection of carbon dioxide and relative humidity using polymer-coated fiber Bragg gratings	Xu, YZ et al. 2022	Polyimide-coated fiber Bragg grating; CO2 sensor; Relative humidity; Cross-sensitivity	SENSORS AND ACTUATORS B-CHEMICAL	Chemistry, Analytical; Electrochemistry; Instruments & Instrumentation
Temperature Compensation Methods of Nondispersive Infrared CO2 Gas Sensor with Dual Ellipsoidal Optical Waveguide	Yi, S et al., 2017	nondispersive infrared gas sensor; carbon dioxide gas sensor; thermopile detector; ellipsoid waveguide; temperature sensor	SENSORS AND MATERIALS	Instruments & Instrumentation; Materials Science, Multidisciplinary
Development of a CO(2)Sensor for Extracorporeal Life Support Applications	Bellancini, M et al., 2020	CO(2)sensor; mid-IR; extracorporeal life support devices	SENSORS	Chemistry, Analytical; Engineering, Electrical & Electronic; Instruments
Spatial and temporal distribution of carbon dioxide gas using GOSAT data over IRAN	Falahatkar, S et al., 2017	Climate change; Satellite monitoring; Interpolation; Land cover; NDVI;	ENVIRONMENTAL MONITORING AND ASSESSMENT	ENVIRONMENTAL MONITORING AND ASSESSMENT
Synthesis and characterisation of cerium sulphide over optical fiber and its gas sensing application Synthese und Charakterisierung von Cer-Sulfid	Theoderaj, AKC et al., 2021	Fiber optic cable; Cerium disulphide; chemical bath deposition; Carbon dioxide detection; Gas sensor; Modified-cladding fiber sensor	MATERIALWISSENSCHAFT UND WERKSTOFFTECHNIK	Materials Science, Multidisciplinary
Measurements of Flammable Gas Concentration in Landfill Areas with a Low-Cost Sensor	Daugela, I et al., 2021	greenhouse gases; methane; regression analysis; sensor calibration;	ENERGIES	Energy & Fuels
A low cost MEMS based NDIR system for the monitoring of	Vincent, TA et al., 2016	CO2 ppm detection; Breath analyis; Metabolic rate; NDIR; SOI; Thermopile detector	SENSORS AND ACTUATORS B-CHEMICAL	Chemistry, Analytical; Electrochemistry;

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Table 2 (*continued*)

Title	Author(s) year	Key words	Sources	Research field
carbon dioxide in breath analysis at ppm levels.				Instruments & Instrumentation
Improving the Accuracy of the Ndir-based Co2 Sensor for Breath Analysis	Prokopiuk, A et al., 2021	NDIR; CO2 sensors; breath analysis; absorption spectroscopy	METROLOGY AND MEASUREMENT SYSTEMS	Instruments & Instrumentation
Sensitivity enhancement by surface texturing of Ag-doped BaTiO3-CuO thin film for CO2 gas sensor	Rudraswamy, SB et al., 2014	Carbon dioxide; Gas sensor; BaTiO3-CuO	2014 CONFERENCE ON OPTOELECTRONIC AND MICROELECTRONIC MATERIALS	Engineering, Electrical & Electronic; Nanoscience & Nanotechnology;
Photoacoustic CO2 sensor system - design and potential for miniaturization and integration in silicon	Huber, J et al., 2015	carbon dioxide; CO2; sensor; miniaturization; photoacoustics; gas sensor; spectroscopy; indoor air quality	SMART SENSORS, ACTUATORS, AND MEMS VII; AND CYBER PHYSICAL SYSTEMS	Engineering, Electrical & Electronic; Optics; Physics, Applied
Nanomaterial-Based CO2 Sensors	Rezk, MY et al., 2020	nanomaterials; CO2 monitoring; gas sensing	NANOMATERIALS	Chemistry, Multidisciplinary; Nanoscience & Nanotechnology; Materials
Electrochemical sensors based on proton-conducting electrolytes for determination of concentration and diffusion coefficient of CO2 in inert	Kalyakin, AS et al., 2021 [77]	LaYO3; Perovskite; CO2 monitoring; Electrochemical cell; Amperometric analysis; Proton-conducting electrolytes	CHEMICAL ENGINEERING SCIENCE	Engineering, Chemical
Chemiresistive Sensor Based on Zinc Oxide Nanoflakes for CO2 Detection	Kanaparthi, S et al., 2019	CO2 gas sensor; ZnO gas sensor; ZnO nanoflakes; environmental monitoring; pollution monitoring	ACS APPLIED NANO MATERIALS	Nanoscience & Nanotechnology; Materials Science, Multidisciplinary
Optical Carbon Dioxide Detection in the Visible Down to the Single Digit ppm Range Using Plasmonic Perfect Absorbers	Pohl, T et al., 2020	PEI; CO2; gas sensing; optical; perfect absorber; refractive index sensing; plasmonic sensing	ACS SENSORS	Chemistry, Multidisciplinary; Chemistry, Analytical; Nanoscience

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