Continuous Emission Monitoring Systems (CEMS) in India: Performance Evaluation, Policy Gaps and Financial Implications for Effective Air Pollution Control

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Abstract

Continuous Emission Monitoring Systems (CEMS) are devices used to measure and report real-time emission of air pollutants. Although CEMS have been extensively deployed in developed countries to ensure compliance with emission standards and enhance their environmental performance, their adoption in India is still in its early stages. The present study aims to evaluate the effectiveness of CEMS in India, identify obstacles in terms of policy, regulation, technology and finance that impede their adoption and suggest mechanisms and incentives to facilitate their expansion. The findings indicate that CEMS offer benefits for air pollution control in India by improving monitoring accuracy, transparency, accountability and enforcement. The study also highlights institutional challenges faced by CEMS, including the absence of a certification system, lack of quality assurance measures, issues with data validation and challenges in its calibration as well as integration concerns with existing regulatory framework. To address these challenges effectively it is recommended that India must develop a policy framework for CEMS along with regulations. Essential steps such as establishing a certification and accreditation system should be taken while enhancing stakeholders' capacity and awareness.

Keywords; Policy gaps; Continuous Emission Monitoring Systems (CEMS); Challenges; Pollution control; Regulation; Technology

1. Introduction

1.1 Background

Industrial emissions are one of the main causes of air pollution in India, which affects the environment and health of the people and releases various pollutants like carbon dioxide (CO2), sulphur dioxide (SO2), nitrogen oxides (NOx) and particulate matter (PM) into the atmosphere. Air pollution causes over 6.5 million deaths annually worldwide and can lead to chronic diseases, impaired brain function, reduced visibility, acid rain and climate change (WHO, 2023). Air pollution has emerged as a pressing concern causing detrimental effects on human health, ecosystems and climate change. To tackle this issue effectively, it is imperative to have precise and ongoing monitoring of emissions. Real-time monitoring plays a role in gathering information to evaluate air quality, pinpoint sources of pollution and develop specific strategies for control (UNEP, 2019; WHO, 2021). Air pollution primarily stems from the combustion of fossil fuels, industrial activities and transportation. These activities release various pollutants like particulate matter (PM), sulphur dioxide (SO_2), nitrogen oxides (NOx), and volatile organic compounds (VOCs) (Kampa & Catanas, 2008).

To safeguard the environment and ensure compliance with regulations, CEMS play a crucial role in monitoring and quantifying pollutant concentrations emitted by industrial processes. CEMS comprise gas analyzers, sample conditioning equipment, calibration tools, maintenance provisions, data acquisition systems and reporting mechanisms (U.S., GPO, 2023; Jahnke, 2022). Regulatory bodies worldwide, such as the Central Pollution Control Board (CPCB) and Government of Canada among others, have issued guidelines and protocols for implementing CEMS to monitor pollution control system performance and guarantee adherence to specified standards (Government of Canada, 2022; CPCB, 2018). Various types of CEMS are available, depending on the parameters to be monitored, sampling techniques and analytical methods are shown in Table 1 (USEPA, 2017).

China conducted a study using CEMS to measure SO_2 levels in ambient air. The findings revealed a significant link between SO_2 exposure and an increased risk of lung cancer, highlighting the important role of CEMS in understanding the health impact of air pollution (Zhang & Schreifels, 2011). As India grapples with severe air pollution issues, there is growing momentum towards adopting CEMS. In response, the CPCB has issued a directive for continuous emissions monitoring to effectively manage pollution from various industries. This initiative aims to evaluate their effectiveness, identify challenges and address policy gaps in India to fight against pollution (CPCB, 2018).

1.2 Global Scenario

Different countries around the world have adopted CEMS at varying levels, depending on their economic, social and environmental conditions. The history of CEMS adoption can be traced back to the 1970s, when the United States was the first country to implement CEMS as a regulatory requirement for power plants and other major sources of air pollution under the Clean Air Act Amendments of 1970. The main reason was to monitor and enforce the emission standards for criteria pollutants such as SO2, NOx, CO and particulate matter (US EPA, 2017).

In the 1980s, the European Union followed the US example and introduced CEMS as a mandatory requirement for large combustion plants under the Large Combustion Plant Directive of 1988. The main reason was to reduce the transboundary air pollution and acid rain in Europe, which had significant impacts on human health and ecosystems. In the 1990s, Japan, Canada and Australia also adopted CEMS as a part of their environmental regulations for various industrial sectors such as power generation, cement, steel and chemical industries. The main reason was to comply with the international agreements on climate change and ozone depletion, such as the Kyoto Protocol and the Montreal Protocol, which aimed to reduce the emissions of greenhouse gases and ozone-depleting substances (CAA, 2023).

China is one of the largest emitters of greenhouse gases and air pollutants in the world. It faces enormous challenges in controlling its industrial emissions and improving its air quality. China has been gradually adopting CEMS since the late 1990s, but its progress has been slow and uneven due to various barriers such as lack of standards, incentives, enforcement, data quality and public awareness. However, in recent years, China has made significant efforts to promote CEMS adoption in key industries such as power generation, steel, cement, petrochemicals, non-ferrous metals, waste incineration and pulp & paper. The main reason was to implement the national action plan on air pollution prevention and control (2013-2017), which aimed to reduce the emissions of major pollutants by 10-25% by 2017 compared to 2012 levels. Moreover, China has also been developing its own standards and technologies for CEMS to suit its domestic conditions and needs (Wang et al., 2019).

Chen et al. (2020) conducted a notable study that emphasizes the importance of China's real-time CEMS monitored data at the source level. Their research highlights three key advantages: Firstly, the ability to directly estimate industrial emission factors and absolute emissions using hourly source-level CEMS data. Secondly, improving the spatio-temporal resolution and representation of heterogeneous and time-varying characteristics of power emissions data and thirdly, demonstrates the potential for other countries to adopt CEMS-based estimation methods for regulating power emissions. The Chinese Industrial Emissions Database (CIED) crafted from up-to-date data from China's emission monitoring systems (CEMS) further enhances precision. By directly calculating emission factors and absolute emissions, this innovative approach minimizes assumptions. Rigorous uncertainty analysis confirms the dependability of the estimates with a margin of error of ±7.2% for factors and ±4.0% for emissions. Providing valuable insights into the concentrations emitted from smokestacks, as well as emission factors and absolute emissions, the CIED stands as a vital tool for researchers and policymakers (Tang et al., 2023). In another study Wang et al. (2023) revealed that the atmosphere in China is heavily polluted by industrial air emissions. These emissions contain ultrafine particles (UFPs), VOCs, NH3, and NOx, which are harmful elements. Consequently, there is now a strong regulatory focus on implementing online monitoring of emission sources. This study also brought attention to advancements in pollution control, as well as the identification of areas prone to high levels of pollution.

It is worth noting that developed countries like Germany, United Kingdom, Japan and the United States dominate the CEMS market with their advanced technology and significant role in imports (MarketWatch, 2023a; MarketWatch, 2023b).

Driven by strict regulations and the need for advanced technology and sensor development, industries such as power generation, oil and gas and chemicals have been mandated by initiatives like Australia's National Pollutant Inventory (NPI) to install CEMS for monitoring and reporting emissions (Manisalidis et al., 2020).

1.3 Current Scenario in India

Due to enforcement of pollution monitoring regulations, the CEMS scenario in India is currently experiencing significant growth. The government, along with regulatory bodies, has taken proactive measures to tackle air pollution and ensure adherence to regulations. Key players in the Indian CEMS market include ABB Ltd., AMETEK, Inc., Emerson Electric Company, Thermo Fisher Scientific Inc., and Horiba Ltd. To address air pollution and enhance solid waste management, the government has introduced initiatives like the National Clean Air Programme (NCAP) and the Swachh Bharat Abhiyan. By 2024, the NCAP has set its sights on a 20%-30% decrease in air pollution levels. It is no wonder that the demand for CEMS in India is on the upswing, due to the efforts made by the NCAP (ABB, 2022). India does not specify all installed CEMS equipment and their operating conditions, but specific data are available for some industries, e.g. 127 factories in the state of Gujarat have installed CEMS equipment. The Indian CEMS market is estimated to be valued at US$ 800-900 million and is mainly focused on monitoring pollutants such as dust, SO_2, NOx and other pollutants. Compared to the United States and Europe, India later adopted CEMS technology to improve environmental management and achieve sustainable development goals (HCGA, 2016).

In India, most of the CEMS devices have been imported from foreign countries. However, CEMS manufacturing is currently underway in India, with companies like Respirer Living Sciences Pvt Ltd (led by Ronak Sutaria) taking the lead in indigenous production. These companies adhere to Indian environmental standards and CPCB guidelines, tailoring the manufacturing of CEMS devices to the specific requirements of the Indian context. To further promote the manufacturing sector for indigenous production of CEMS devices, the government of India has some schemes. One of them is the Atmanirbhar Bharat ('Self-Reliant India') Programme, which is a government initiative to enhance the competitiveness, efficiency and exports of Indian manufacturers by attracting investments in advanced technology and creating economies of scale. One of the components of this programme is the Production-Linked Incentive (PLI) scheme, which offers various incentives to different sectors of the economy. The Scheme for Promotion of Manufacturing of Electronic Components and Semiconductors (SPECS) is a PLI scheme that could help to promote indigenous manufacturing of CEMS in India. The SPECS scheme offers a 25% capital subsidy on a reimbursement basis for a period up to five years to companies that invest in plant, machinery, equipment, utilities, R&D and technology transfer for manufacturing CEMS and other electronic goods. The scheme is applicable to both new units and expansions and is open for applications for three years. The scheme has a transparent application and disbursement process, which involves the submission, examination, acknowledgement, appraisal and approvalby the Project Management Agency (PMA). After approval, the companies can submit their claims, which will be verified by the PMA and then disbursed. The SPECS scheme is expected to boost the domestic production of CEMS in India. The application process and Claim for Disbursement of Incentive to avail this scheme are shown in Figure 1 (Invest India, 2023; SPECS, 2023).

According to Greenstone et al., (2020), there had been about 1,000 CEMS devices installed in India as of 2018, overlaying about 10% of the industrial emissions sources. It is also mentioned that installation of CEMS devices increased by 50% from 2016 to 2018, indicating rapid growth in the CEMS market (Figure 5). According to the CPCB, there have been about 2,500 industries that installed CEMS as of February 2020, out of which about 1,500 were linked to the CPCBs online portal. The CPCB additionally said that it had issued guidelines to approximately 4,000 industries to install CEMS via March 2020 (3ie, 2020). According to the CSE evaluation, there had been approximately 17 SPCBs that shared their CEMS data in public domain as of October 2020, covering approximately 50% of the state pollution authorities in India.

The evaluation additionally identified that most industries have been working in offline mode, meaning that their CEMS statistics were no longer transmitted in actual time (Down to Earth, 2022).

According to a report of Mission Energy Foundation, CEMS in India is expected to develop at a CAGR of 12% from 2018 to 2023, attaining a market of USD 800-900 million by 2023. They also said that CEMS in India is predicted to cover about 30% of the Industrial emissions sources by 2023, up from 10% in 2018 (Mission Energy, 2023). According to ENVEA, a global leader in environmental monitoring solution, CEMS in India is expected to enhance its environmental governance with the aid of concerning global technology and solution providers under a roof, bringing like-minded discussions, technical sessions and a gambit of networking possibilities. ENVEA additionally said that CEMS in India is predicted to provide recommendations, technical help and realistic solutions to help operators to meet environmental objectives (ENVEA, 2023).

The Press Information Bureau report (PIB) of the Government of India (GoI) reveals that from 2014 to 2022, only 712 out of 4,247 industrial units have failed to connect their Online Continuous Emissions Monitoring Systems (OCEMS) to the servers of the CPCB and the SPCBs. These units are under closure orders for not complying with the environmental standards and self-regulation norms. The category-wise OCEMS connectivity status is given in Table 2 (PIB, 2022).

In the same PIB report, it is also mentioned that there are 3758 (functional) highly polluting industries under the CPCB guidelines for 17 categories of industries in India. Out of which 3430 industries installed CEMS and transferred their data to CPCB as per complying environmental standards, and for the rest of the 328 industries, appropriate action has been taken for non-complying with the environmental standards (PIB, 2022).

The Ministry of Environment and Forests in 2011 has initiated an important project to design and evaluate a pilot emissions trading scheme (ETS) for particulate matter from stationary sources in collaboration with three states- Gujarat, Maharashtra and Tamil Nadu with the CPCB as the nodal agency for overall implementation of the program. This has been initiated as a way forward towards reducing particles in the ambient air. Therefore, the role of CEMS is to measure the total load of particulate matter (PM) coming from each stationary source. The implementation of CEMS in India started in 2013, when the CPCB initiated the process of mandating CEMS for major industries and common pollution treatment facilities. In February 2014, the CPCB issued a direction to install real-time effluent quality monitoring systems in 17 categories of highly polluting industries and common pollution treatment facilities. In March 2014, the MoEF&CC issued a draft notification on the use of CEMS for monitoring and reporting of emissions and effluents. However, the draft notification was put on hold in April 2015. By March 2016, nearly 80% of 2764 plants had already installed or were in the process of installing CEMS. In August 2017, the CPCB released guidelines for implementing CEMS, specifying how suitable monitors will be selected, installed, operated and meet compliance requirements. The guidelines were revised in August 2018, incorporating more details on monitoring technologies, calibration, performance evaluation and data management. In August 2019, the NPL was appointed by MoEF&CC as a certification body for CEMS, but the certification system was still in the developing phase.

1.4 Scenario in Uttar Pradesh

The installation of CEMS in Uttar Pradesh (UP) has primarily been observed in thermal power plants. During a survey conducted in thermal power plants in Uttar Pradesh, it was noted that CEMS systems have been installed on each unit. However, data calibration is required to ensure accurate measurements. The Uttar Pradesh Pollution Control Board (UPPCB) has conducted inspections of various industries to enforce compliance with emission limits. During these inspections, it was found that CEMS systems were operational, indicating their use in monitoring and controlling emissions. The implementation of strict rules and regulations regarding pollution monitoring across industries is expected to drive the demand for CEMS in Uttar Pradesh. The certification system for CEMS in India necessitates well-framed certification and quality assurance systems, along with corresponding guidelines and protocols. The installation of CEMS devices in various industries across Uttar Pradesh is anticipated to assist these industries in complying with emission limits and reducing the release of pollutants. The presence of CEMS in thermal power plants and the emphasis on pollution monitoring regulations indicate the potential demand and utilization of CEMS systems in the state. The implementation of stringent pollution monitoring regulations is expected to generate further demand for CEMS across industries in the State (CSE, 2019; CSE, 2022).

According to the CPCB real time data monitoring system (RTDMS), there are 452 industries in Uttar Pradesh that have installed CEMS to measure and report their emissions in real time enabling tracking their emissions through real-time data monitoring systems. However, as per analysis done by Directorate of Environment, only 279 industries have shared their data with the CPCB, while the remaining 173 have not. This indicates that there is still a major challenge in acquiring real-time data from all the industries.

The survey used a random sampling method to collect questionnaire responses from 55 industries in Uttar Pradesh. The survey found that most of the industries (96.67%) already use CEMS, indicating high adoption. The remaining 1.7% are planning to install CEMS soon, showing potential growth. This data reflects a positive trend in CEMS adoption, driven by environmental awareness and compliance needs.

This research paper aims to comprehensively analyse the implementation and performance of CEMS in India with particular reference to State of Uttar Pradesh. The study also examines the challenges encountered during CEMS implementation, such as high cost, technical limitations, lack of calibration facilities, indigenous certification system, data management issues and maintenance concerns. Additionally, it evaluates the existing policy frameworks while identifying gaps that require attention for successful implementation and widespread adoption of CEMS in India. By addressing these research objectives, this study will provide valuable insights for policymakers, regulatory bodies, industries and researchers involved in air pollution control efforts. The findings of this report will contribute to the development of informed policies, improved CEMS implementation strategies and overall enhancement of environmental management in India and in Uttar Pradesh.

2 Methodology

A detailed literature review was conducted on the work that has been done on the continuous emission monitoring system (CEMS) in India. This study used a comprehensive methodology, commencing with an in-depth literature review on performance evaluation, policy gaps and financial implications for effective air pollution control through CEMS in India. The review of secondary data showcased multiple aspects, including policy frameworks, challenges, calibration services and data monitoring-related status of CEMS in India. With the help of scholarly search engines such as Google Scholar, PubMed, ScienceDirect, ResearchGate, Scopus, and SciFinder, web addresses, published reports, government websites, surveys etc. were utilized to gather authoritative sources of secondary data on CEMS. This research paper covers the global CEMS scenario, examining its current status, challenges, calibration costs, financial gaps, data monitoring issues and adherence to Central Pollution Control Board guidelines (CPCB). The compilation of references drew from a diverse array of secondary sources, including web pages, blogs, research papers, published reports, surveys and concise articles. In addition to this, we conducted a questionnaire-based survey with various industries in UP and also organized stakeholder's consultation with CEMS experts on May 17 and 19, 2023, to gather information about the current status of CEMS in India and these findings have also been integrated into this report.

In total, 130 original articles incorporated into the analysis. The presentation of data, achieved with precision and clarity, adhered to the journal's standards, with tables and figures created using Microsoft PowerPoint, Excel and Word software applications.

3 Policy and Framework

3.1 Global Level Policy and Framework

The adoption of CEMS varies across different countries and regions, depending on the level of economic development, environmental awareness, political and global influence.

The United States has been at the forefront of adopting and implementing CEMS as a key component of environmental policies. This commitment to monitoring and regulating air emissions is evident in the Clean Air Act (CAA) and its amendments. Under the CAA, the U.S. Environmental Protection Agency (EPA) has defined specific requirements for the installation, certification, operation and maintenance of CEMS for various pollutants, including sulfur dioxide (SO_2), nitrogen oxides (NO_x), carbon dioxide (CO_2), oxygen (O_2), etc. These standards aim to ensure the accurate measurement and reporting of emissions, a fundamental aspect of effective pollution monitoring and reduction (EPA, 2017).

The EU's approach to CEMS adoption is reflected in the Industrial Emissions Directive (IED), which sets forth comprehensive requirements for monitoring emissions from industrial facilities. The IED mandates the use of CEMS to monitor emissions from a wide range of industrial activities, including energy production, waste management and chemical processing. Furthermore, the EU has established the European Environment Agency (EEA) to oversee environmental issues, including emissions monitoring. The EEA compiles data from member countries, assesses the environmental impact and supports the implementation of consistent standards and best practices across the European Union (EU, 2021).

Policies on emissions monitoring are essential to reduce coal fire power plants (CFPs) emissions and their harmful impacts. Emissions monitoring provides environmental control agencies access to more information which serves as the basis for regulators to determine whether regulated facilities comply with emission standards or not (Clean Air Asia, 2020). Continuous emissions monitoring, when properly used and maintained, can strengthen the regulator's capacity to effectively and enforce emission standards would reduce the need for onsite inspection and manual reference method tests (Jahnke, 2022). The major economies and top coal consuming countries in the world implement policies requiring the use of CEMS as part of their emissions regulation programs for power plants and industrial facilities. Governments can regulate point sources of air pollutants by using CEMS data to support pollutant registration, pollutant discharge permitting and operation regulation, which includes the temporary shutdown of facilities exceeding emission standards. Air pollution regulations in China also use CEMS data to implement a pollution levy system for power and industrial facilities (Zhang et al., 2011). Apart from the regulatory aspect of monitoring, existing policies on the use of CEMS state that the CEMS data are to be used to verify the types and volume of emitted pollutants. It can also help in tracking ambient air quality and the potential air pollutants. The CEMS policies of Asian countries have stipulations typically based on guidelines from international and foreign agencies, such as the European Union (EU), European Commission (EC), The United States Environmental Protection Agency (US EPA) and the Organization for Economic Cooperation and Development (OECD). Generally, these specifications have detailed guidelines on the monitoring of individual pollutants and the performance of the CEMS technologies. In Thailand and the Philippines, for instance, CEMS implementation guidelines (particularly on the data reporting requirements) are based on specifications from the US EPA. The Implementing Rules and Regulations of the Clean Air Act (or Department Administrative Order No. 2000-81) of the Philippines environmental agency utilizes the CEMS related policies of

Asian countries and also establishes platforms where data can be gathered and stored for use in emission analysis and regulatory activities. Depending on the policies and technological advancements of the countries, these platforms may already be using automated data acquisition and storage systems and thus may require sources to submit data more frequently. China, Thailand and Philippines are countries with established central data acquisition and management systems, where regulated sources equipped with CEMS can regularly submit emissions data. These central data handling systems such as; China Emissions Accounts for Power Plants (China), Pollution Online Monitoring System (Thailand) and Data Acquisition and Handling System (Philippines) are already connected to a substantial number of industrial and power facilities in the countries. In terms of emissions data reporting, policies of the various countries that were reviewed require the CEMS data to be regularly reported. Common to all reviewed policies, regulated emission sources are required to submit full emissions reports at least twice a year or quarterly. In some cases, the frequency of reporting will depend on the pollutant types being reported, as in Vietnam's Law on Environmental Protection (LEP) 2020 and Decree No. 08/2022. For the countries with established central data management systems, such as Thailand and the Philippines, the regulated facilities are also required to transmit their CEMS data, as well as the updated closed circuit television photo capture of the stack, every five minutes or on an hourly basis. One significant benefit of these policies that require the use of CEMS is the improvement of regulatory process efficiency. With the CEMS data readily available at any given time, regulators and facility operators can be quickly alerted, either by the CEMS or by the regulator's central data handling system, about any exceedances of the monitored facilities over the pollutant emission limits. The regulators can then use this information to send out notifications or warnings, as well as any corresponding penalties, to the facility operators for corrective action. The installation and operation of CEMS are governed by various regulations. The Part 75 rule outlines the specific requirements for installing, certifying, operating and maintaining CEMS, covering pollutants such as SO_2, NOx, CO_2, O_2, etc. Sources subject to permit requirements or state regulations must adhere to the state specific guidelines. To ensure accurate measurement and reporting of emissions, each CEMS is required to complete a cycle of operation every 15 minutes. Compliance with these regulations is crucial for effective pollution monitoring and reduction in the USA (CAA, 2023).

3.2 CPCB Guidelines for CEMS

To combat air pollution, the Central Pollution Control Board (CPCB) has issued directives under Section 18(1) (b) of the Water (Prevention and Control of Pollution) Act, 1974, and the Air (Prevention and Control of Pollution) Act, 1981. These directives are aimed at ensuring environmental compliance in the industrial sector by instructing State Pollution Control Boards (SPCBs) and Pollution Control Committees (PCCs) to direct industries falling under 17 highly polluting categories, as well as Common Effluent Treatment Plants (CETPs) and facilities for biomedical and hazardous waste, to install online monitoring systems. These actions align with the objective of monitoring and controlling pollution.

Furthermore, the CPCB has issued additional directions under Section 5 of the Environment (Protection) Act, 1986, specifically for industries within the 17 highly polluting categories, mandating the installation of continuous emission and effluent monitoring systems (OCEMS) and the establishment of data connectivity with SPCBs/PCCs and CPCB servers. In cases where existing industries within these categories are found to operate without OCEMS, SPCBs/PCCs are instructed to issue closure orders. For new establishments within these categories commissioned after February 28, 2017, a specific condition of installing and connecting OCEMS must be included in the Consent to Operate (CTO).

As per mandatory regulations, the installation of CEMS is required for 17 categories of highly polluting industries and biomedical/hazardous waste incinerators. These industries are responsible for data submission, facilitated by instrument suppliers who install servers in regulatory bodies to enable seamless data transfer from CEMS. To enhance efficiency, it is recommended to establish a unified protocol for direct data transfer. Additionally, industries must secure 5-year maintenance contracts with authorized service partners, ensuring timely issue resolution within 72 hours, spare parts availability for 7 years and calibration validation (CPCB, 2017). Furthermore, according to the CPCB 2018 guidelines, specific industries utilizing boilers, such as Sugar, Cotton Textile, Composite Woollen Mills, Synthetic Rubber, Pulp & Paper, Distilleries, Leather Industries, Calcium Carbide, Carbon Black, Natural Rubber, Asbestos, Caustic Soda, Small Boilers, Aluminium Plants and Tanneries are also mandated to install CEMS. To promote self-regulation, it is recommended to introduce the concept of CEMS beyond highly polluting industries, encouraging other sectors to consider installing CEMS for self-regulatory purposes. As a technological advancement, cloud-based server installation is suggested, where providers would install their servers in the cloud and transmit real-time data to CPCB, SPCBs or other government bodies in consultation. This approach signifies a shift towards cloud-based data management and transmission (CPCB, 2018).

CPCB issued the first guidelines for CEMS in 2014 and revised them in 2017. Further, it added some more industries in 17 categories of industries in 2018 and revised their guidelines again. The guidelines aim to provide a framework for implementing CEMS to monitor and report emissions from various industries in real time. The guidelines for implementing the CEMS in India are as below in Figure 3. (CPCB, 2018).

4 Challenges

4.1 Policy and implementation Gaps

Implementation of CEMS in India has revealed several policy gaps, which were identified through research reports, surveys, including the questionnaire-based survey, as well as stakeholder consultation in CEMS ecosystem under this research. Some of these gaps are shown in Figure 10 (CSE, 2016; DoE, 2023). Though CEMS regulations have been brought in quite early in 2014 but a comprehensive policy for CEMS adoption addressing its complete value chain including the issues related to costs, indigenous certification system, accreditation of labs for periodic CEMS calibration, data validation & transparency, use of CEMS for regulatory purposes, green skill development for CEMs operation & maintenance etc. is needed (DoE, 2023).

4.2 Financial Gaps

Financial challenges faced by industries in implementing CEMS in India are multifaceted. The high cost of CEMS, encompassing equipment procurement, installation and personal training poses a significant obstacle, particularly for small and medium-sized enterprises. Additionally, the absence of essential infrastructure such as detailed guidelines, device certification and lab empanelment, increases implementation costs and hinders regulatory compliance. The lack of a certification system for industrial emissions monitoring devices further undermines the credibility of the monitoring system, potentially resulting in unreliable data (CSE, 2015; Kanchan & Bahel, 2016). Ensuring the long-term sustainability of CEMS demands continuous funding for operation, maintenance and upgrades which can be challenging for industries in India. Moreover, investing in adequate training and capacity building programs for operators and technicians constitutes another financial hurdle for industries seeking to establish effective and reliable CEMS implementations. Addressing these financial challenges is crucial for successful CEMS adoption and environmental compliance in India (Greenstone et al., 2020).

CEMS implementation in India faces several challenges, especially for small scale industries, which are vital to the progress of the country. Small scale industries account for more than 40% of the gross industrial value added of the Indian economy and contribute significantly to employment generation and rural industrialization. Due to their low capital intensity and high labour absorption, small scale industries have become the backbone of the Indian economy (Shylaja, 2014). Small-scale industries in Uttar Pradesh faced obstacles when trying to install CEMS. These challenges included a lack of awareness about CEMS benefits, high installation costs, issues with data accuracy and inadequate infrastructure like power and internet connectivity. Non-compliance with pollution control guidelines was also common due to weak enforcement. Industry associations and stakeholders were resistant to CEMS adoption due to fears of increased regulations. These challenges made it difficult for small-scale industries to embrace CEMS technology and meet environmental standards (ED, 2018; YAL, 2019 & JETIR, 2020).

The survey conducted by DoE identified that the most common challenge in installing CEMS is the high initial investment and maintenance costs, mentioned by a significant majority of respondents. The lack of clear regulatory guidelines and standards is another obstacle. Additionally, a notable number of respondents cited a lack of technical expertise and support as a challenge. Some respondents face a combination of these challenges, highlighting the complexity of CEMS installation issues. Addressing these challenges may require a multifaceted approach, including cost reduction strategies, improved regulatory guidance and investments in training and technical support for CEMS implementation in the industry.

It also shows that most respondents (87.5%) are aware of the capital costs of CEMS installation in their industries, indicating good financial knowledge. However, about 12.5% are not aware, possibly due to varying roles in organizations. This suggests a need for internal communication and training to bridge this knowledge gap. The data underscores the importance of educating all stakeholders on these costs for informed decisions in emissions monitoring and compliance (Figure 8A-8B).

4.3 CEMS Installation, Operation, Maintenance and Calibration

CEMS Operational conditions vary for different industries for a given source category, making the choice of monitoring equipment unique to each installation. The choice of monitoring system depends on the physical and chemical properties of the pollutant, waste gas stream, regulatory or permitting limits, location and method of collecting, processing and disposing of samples, calibration and accuracy requirements, quality assurance and control, maintenance, facility safety and management (Clarke, 1998). CEMS are categorized into two groups: In-situ or non-extractive CEMS (wet basis) and Extractive CEMS (dry or wet basis). In-situ CEMS utilize analyzers and sensors that are directly installed in the stack and come into direct contact with the gas being measured. This eliminates the need for gas extraction and transportation. The key advantages of in-situ CEMS include measuring emissions under the same conditions as the gas in the stack, eliminating the need for probes or heated lines for sample collection, transportation and eliminating the requirement for a conditioning system. On the other hand, Extractive CEMS require the extraction of gas from the stack using vacuum pumps and its transport to the analyzers without altering its composition (USEPA, 2000).

According to EPA-CAM Rule, there are two monitoring options for source compliance: continuous emissions monitoring (CEM) and parametric monitoring. CEMS directly measures pollutant concentration from a duct or stack, while parametric monitoring indirectly measures emissions by monitoring key parameters related to air pollution control or process equipment. However, parametric monitoring requires a demonstration of correlation between monitored parameters and measured pollutants for small emissions. EPA has published standard methods for installing, operating and testing CEMS. EPA rules specify the reference methods that are used to substantiate the accuracy and precision of the CEMS. The EPA also maintains performance specifications used for evaluating the acceptability of the CEMS after installation. Finally, the rules provide quality assurance and control procedures to evaluate the quality of data produced by CEMS once in operation (USEPA, 2020).

CEMS are operated and maintained by third parties with support provided by the plants while large power plants often operate CEMS in house. Nearly all CEMS operators have established developed CEMS operation and maintenance routines. However, in the absence of systematic onsite inspection of

CEMS operation, it is unclear how these rules have been followed in practice. Many officials believed that only few CEMS operators regularly perform calibration and reference tests. The third-party operation of CEMS, which must be certified by a certified laboratory, is an effective means to ensure standardized operation and improved accuracy of data. Many facilities also assign employees to assist in the CEMS operation, including screening CEMS data, documenting operation and maintenance activities and discovering and referring problems to the operators (Zhu et al., 2000).

The operation and maintenance of CEMS can be time consuming and technically demanding if not properly implemented. Although CEMS staff are trained and certified, many lack the necessary expertise to properly operate, maintain and quality assure the equipment. CEMS operators need to establish a set of routine CEMS operation and maintenance rules and to keep onsite documentation of related activities. Some facilities have only a few pages of rules, while others have a relatively comprehensive set of rules. They do not appear to be any guidance or standards for the written rules that guide CEMS operators in operating and maintaining the CEMS (Shen & Gao, 2008; Le, 2004; Zhu et al., 2000). The EPA has published standard methods for installing, operating and testing CEMS, while rules specify reference methods to substantiate them, ensuring data accuracy (EPA, 2009; EPA, 2022).

According to a study of power plants in Zhejiang Province, CEMS were seldom calibrated and when calibration was done, it was generally done manually. Even facilities with automatic calibration typically conduct manual calibration because they can bypass the sampling system, which reduces the amount of calibration gas used, thereby reducing costs. However, by only calibrating the analyser, any problem in the sampling and conditioning system will not be discovered. One local emission measurement center (EMC) reported that many facilities relied on the EMCs reference tests (typically conducted one to four times per year) to calibrate the CEMS. In other words, those facilities do not calibrate their CEMS regularly as required (Le, 2004).

Calibration gas quality is a critical factor for CEMS calibration and inconsistent calibration gas quality was identified in a study conducted across the regions of Guangdong Province in China. The Ministry of Environmental Protection (MEP) regulations do not provide specific protocols for calibration gases to ensure consistent quality and the gas vendors only need to obtain a license for chemical production to be eligible to manufacture and sell calibration gases. In some regions, the environmental protection bureaux (EPBs) designate authorized gas vendors from which facilities can purchase calibration gases (Yu et al., 2000).

Calibration gases should represent the typical pollutant concentrations in the flue gas at the facility. The type of CEMS and the presence of pollution controls can also affect the choice of pollutant concentration in the calibration gas. Power plants with desulphurization equipment typically use a ‘‘dual span’’ and calibrate with low and high concentrations to represent controlled and uncontrolled periods.

This approach is recommended by the US Environmental Protection Agency Part 75 CEMS regulation (US EPA, 2009).

In a study, during facility visits some conditions are visually identified that affect CEMS data accuracy, such as standing water in looped sample lines that absorbs SO2 and NO2 in the sample, air leaks in sample lines enabling ambient air to infiltrate thereby reducing the pollutant concentrations and lack of temperature controls in the CEMS shelter resulting in increased potential for calibration drift of the analysers. There are simple, inexpensive solutions to these problems, but the government must provide the proper incentives, to implement the solutions (Shen and Gao, 2008).

In another study, about half of the CEMS were operating normally but even these CEMS failed one or more of the EMCs tests. The Chinese government and industry have made significant progress in monitoring and reducing emissions, particularly with regard to emissions from state controlled key polluting facilities such as power plants. The study also suggests that implementing an accreditation program for training institutions and standardized certification tests for CEMS operators, testers and government inspectors to ensure a minimum level of competency. The existing MEP regulations and technical guidelines provide details and directions for CEMS operators and EMC inspectors, but there are opportunities to enhance the regulations to improve the consistency of CEMS operation and maintenance and on-site CEMS inspection. The quality of calibration gas is critical to ensure accurate measurements of emissions (US EPA, 1997).

The use of unstable or low-quality calibration gas by numerous CEMS operators, combined with their reluctance to utilize calibration gases due to cost constraints, poses significant challenges to the accuracy and reliability of emissions monitoring systems. Power plants are required to regularly calibrate the CEMS using the appropriate concentration of high-quality calibration gas. EPBs might consider redirecting some of the financial assistance to provide standard calibration gas to all CEMS operators. EMCs could collect information about emissions and stack gas flow with some additional operating parameters to assess the quality of the emission data and identify possible problems through electronic data audits. The quality of calibration gas is critical to ensure accurate measurements of emissions (Boze, 2009; Boze, 2010).

In the field of maintenance strategies, Reliability Centred Maintenance (RCM) is a systematic approach that considers factors such as system life, operating efficiency and maintenance cost-effectiveness. In a study, the RCM approach was used to the sampling subsystem of CEMS to develop maintenance strategies. The approach utilizes Failure Mode and Effect Analysis (FMEA) to identify failure causes and weak components within the sampling subsystem. Based on the FMEA results, maintenance mode decisions are made and an average availability model is introduced to establish a reasonable maintenance interval cycle. The resulting maintenance outline serves as a theoretical basis for factories to enhance equipment reliability and devise effective maintenance strategies (Ya et al., 2021).

Yang et al., (2020) presented an approach for evaluating the reliability of CEMS considering Common Cause Failures (CCFs) employing a combination of fuzzy Failure Mode Effects and Critically Analysis (FMECA) along with Bayesian Network (BN). It presented a more refined estimation of the credibility of CEMS when confronted with CCFs. Employing this method assists in detecting weak elements and providing recommendations for improving their reliability, coupled with preventive servicing. When compared to methods that do not take CCFs into account, the proposed approach enhances the accuracy of reliability assessment for CEMS. The α-factor model within the BN-based reliability model of the sampling system is capable of evaluating the probability of CCF. By using this method, engineers and researchers in the CEMS field can increase system reliability and minimize the possibility of failure (Yang et al., 2020).

In addition, a study focuses on developing predictive models for NOx emissions from cogeneration natural gas plants. The authors used Python-R to train and test nine prediction models based on neural networks. All models meet the regulatory precision requirements, with the best-model predictive models achieving a mean absolute error of 0.5982, an R-value of 0.9451 and a 0.14% difference between measured and predicted emission values using the test dataset. This study demonstrates the feasibility of using open-source machine learning libraries for PEMS development and provides guidance for facility operators to create their own PEMS models for emissions monitoring. Moreover, the study offers a comprehensive comparison of different network structures and optimisation methods, aligning with the regulatory requirements of the US EPA. The findings contribute to wider adoption of predictive models, leading to cost reductions in the industry, as the open-source library allows anyone to replicate the study tests and construct their own models following the provided procedure (Si et al., 2019).

A novel calibration device has been developed for the continuous monitoring of flue gas emissions from stationary pollution sources. The device comprises a shell, a gas distribution system and an infrared gas analysis system. The gas distribution system includes a diluent gas bottle, a standard gas bottle and a gas mixing chamber, while the infrared gas analysis system consists of a SO2detection chamber, a NOx detection chamber and an oxygen sensor. This device improves field operating efficiency and exhibits high practicality and intelligence. The method utilizes online membrane extraction followed by gas chromatographic analysis. VOCs selectively permeate through a membrane into an inert gas flow, where they are trapped, concentrated and subsequently introduced into the gas chromatography column. Continuous monitoring is achieved by periodic injections of samples as the air stream continuously passes through the membrane module (Wenshuai et al., 2021).

The major challenge in CEMS installation is the technology selection such as the appropriate sampling method and analyser technique for the specific pollutant and source. Each technique has its own principle of operation, range of detection, accuracy, precision, response time, calibration frequency, etc.

Therefore, the selection of the analyser technique depends on the type and concentration of the pollutant to be measured, as well as the performance requirements of the CEMS. The other challenge is the determination of the optimal sampling location and number of measurement points in the stack. The sampling location should be representative of the average emission concentration and flow rate of the source and should avoid areas where there are turbulence, stratification, leakage or dead zones. The number of measurement points depends on the size and shape of the stack, as well as the variability of the emission concentration across the cross-section (USAID, 2020; CSE, 2022; DoE, 2023).

Successful CEMS implementation relies on standardized procedures and the quality of data generated. For that purpose, a code for empanelled laboratories is mandatory for proper regulation of CEMS in India. CPCB is formulating a code of conduct or a set of guidelines for the laboratories that are involved in installation, operation, maintenance and calibration of CEMS. However, without a code of empanelled laboratories, there is no uniformity or consistency in the way the CEMS are operated, maintained and calibrated. This can affect the quality and reliability of the emission data and lead to errors and discrepancies. Therefore, it is necessary for the CPCB to develop a code of empanelled laboratories that specifies the criteria, procedures and responsibilities for the laboratories that are engaged in the CEMS activities. The code of empanelled laboratories should also define the roles and functions of the CPCB, the State Pollution Control Boards (SPCBs) and the Pollution Control Committees (PCCs), third party verification agencies in overseeing and verifying the CEMS performance. The code of empanelled laboratories should be based on the best practices and standards available in the field of CEMS and should also be periodically reviewed and updated to incorporate the latest developments and innovations. CPCB in 2019 already designed the "Draft Proposal for Empanelment of Laboratories for CEMS Related Activities" for laboratory empanelment in India for (CEMS) related activities which are still under process (Vinod Babu, CPCB, 2023).

Until the proper empaneled laboratories are not established by CPCB, for various CEMS-related tasks including testing, installation, operation, calibration checks and third-party verification, international standards for empaneled labs (ISO 17025) should be followed.

The main challenge in CEMS operation involves ensuring the quality assurance and quality control (QA/QC) of the data generated by the system. The calibration cost of CEMS is highly variable, often expensive and time consuming. This is primarily due to the distance of the calibration lab from CEMS installations. Many of these labs lack accreditation from the National Accreditation Board for Testing and Calibration Laboratories (NABL), which limits their credibility. As a result, calibration costs can vary, lacking standardization. Furthermore, in many industries, there is a lack of regular checks and periodic calibration, which contributes to the data generated by CEMS not being as authentic and reliable as desired. (DoE, 2023).

A systematic audit process, including evaluations like cylinder gas audits (CGA), linearity tests and relative accuracy test audits (RATA), which serve to validate the accuracy and reliability of CEMS, is notably absent. On the maintenance front, there is a lack of trained personnel, particularly those with the requisite training or certification to manage complex or specialized CEMS. Some maintenance personnel also encounter difficulties in accessing or diagnosing CEMS due to their location or intricate configurations (DoE, 2023).

There is lack of standardization and certification of CEMS devices and technologies in the type, quality and performance used by different industries. There is also no accreditation or certification system for CEMS devices and technologies in India. This leads to difficulty in selecting, installing and operating suitable CEMS devices for different emission sources and pollutants (CSE, 2022).

During the stakeholder discussion held under this research, it was identified that local vendors are deceiving industries. They do this by selling sensor-based devices that are not officially approved by the CPCB. These vendors make false claims that their devices adhere to CPCB standards. In reality, however, these devices lack the essential qualities of reliability, accuracy and durability. This results in, these devices often falling short of meeting emission standards, leading to the wastage of resources, money and time for the industries.

Inadequate facilities for auto calibration, zero check and span check of CEMS devices pose another challenge because calibration is the process of adjusting the CEMS device to ensure that it measures the emission accurately. Zero check and span check are methods of verifying the calibration of the device. However, many industries do not have proper facilities or equipment for auto calibration, zero check and span check of their CEMS devices. This affects the data quality, compliance and enforcement of CEMS in India (DTE, 2022).

The high operation and maintenance costs of CEMS devices continue to challenge industries. Regular maintenance, cleaning and replacement of parts and consumables are essential for maintaining optimal device performance. These activities come at a significant cost, particularly for industries with numerous emission sources and pollutants to monitor. Moreover, CEMS devices are exposed to corrosive gases, vibration and high temperatures that can damage them over time (Greenstone et al., 2020).

The limited utilization of CEMS data for decision-making is a prevailing issue. This data holds the potential to offer valuable insights for both industries and regulators in their efforts to monitor, control and mitigate emissions. Unfortunately, there exists a deficiency in the analysis, interpretation and feedback mechanisms necessary to harness CEMS data for effective decision-making. Furthermore, there's a lack of data transparency and public disclosure, which hinders the promotion of awareness and accountability among stakeholders. The main challenge towards this is the data validation due to lack of a robust CEMS ecosystem that includes periodic calibration and proper operation and maintenance (DoE, 2023).

The questionnaire-based survey in operating and maintaining CEMS in industries done by DoE, revealed key concerns among respondents. A significant number highlighted technical issues about sampling, analysis and data transmission challenges, emphasizing the complexity of emissions monitoring technology. Operational problems, including power supply, safety and accessibility, also occurred as significant hurdles that directly impact CEMS reliability. Regulatory issues, such as compliance and reporting, underline the importance of staying up-to-date with evolving environmental standards. Notably, many respondents faced a combination of these challenges, suggesting a wide array of problems in effective CEMS management. When assessing employee training for CEMS, 82.1% of respondents confirmed their employees received training, while 17.9% reported no training. This diversity in training approaches within surveyed industries suggests some are well-prepared for regulatory compliance and accurate emission data, while others require more attention to ensure proper employee training for CEMS operation and maintenance (Figure 9A-9B).

In our survey, we looked at how industries calibrate their CEMS devices. The results show that most industries, nearly all of them, prefer to use calibration services offered by labs or vendors. This means they hire experts from outside to make sure their CEMS devices are accurately calibrated. It's the common choice among the surveyed industries. Interestingly, there was one company that said they do their calibration in-house. This suggests that only a few industries have the resources and know-how to do calibration internally, giving them more control over the process. The fact that most industries rely on external calibration services shows that they trust the expertise and precision of these specialized service providers. It also shows that calibrating CEMS devices is a complex job that needs special equipment and knowledge. We also investigated whether industrial facilities using CEMS have calibration experts nearby or not. We found that 37.5% of these facilities do have local calibration experts, offering convenience and potentially calibration services. However, 48.2% of the respondents do not have calibration experts nearby, which means they may need to rely on experts from a more distant location. Interestingly, 14.3% of the respondents were uncertain about the presence of nearby calibration experts, suggesting a lack of awareness about local calibration services. To understand opinions about having a calibration facility nearby the industries will help for calibration of CEMS or not. A large majority (87.3%) expressed a strong belief in the benefits of proximity to such a facility, while a smaller group (12.7%) disagreed. This clearly underlines the need and potential advantages of local calibration services in enhancing the efficiency of emissions monitoring, data validity and regulatory compliance efforts, highlighting the value organizations place on convenient support for maintaining and optimizing their CEMS devices (Figure 10A-10C).

4.4 Certification System

Lack of infrastructure, such as clear guidelines, device certification and lab empanelment, hinders the certification of CEMS in India. Still, measures are being implemented to confront these challenges and enhance the certification process. The absence of infrastructure can lead to higher certification costs, making it challenging for industries to meet regulatory requirements. However, with proper investment and development, these challenges can be overcome. CEMS quality and calibration are crucial factors for certification. The standard EN-15267 serves as the framework for a certification system that encompasses all of Europe, developed by the EU. India lacks a standardized certification process for industrial emissions monitoring devices. The accuracy and reliability of monitoring equipment can be uncertain, causing doubts.

In India, ensuring the certification of CEMS is challenging mainly because of the substandard data quality. The absence of standardized protocols and procedures may result in inaccurate data collection and reporting. The accurate assessment of pollution and its effect on the environment is hindered by this. Poor data quality can also obstruct the effective formulation of environmental policies and decision-making. The primary reasons for the difficulties in CEMS certification in India are due to insufficient guidance, instruction and knowledge. Overcoming these challenges is achievable with the right training and guidance. Lower data reliability among stakeholders can be a result of implementing CEMS in India being challenging. Lack of infrastructure, certification, and data quality can hinder the monitoring systems credibility and compliance with regulations (CSE, 2016; CSE, 2018).

A standard certification system for industrial emissions monitoring devices is urgently needed in India to address these challenges. The certification process should include detailed guidelines, device certification and lab empanelment. The establishment of capacity building programs can be considered to educate personnel on the effective operation and maintenance of CEMS. Collaboration between industry associations, academic institutions and regulatory bodies can facilitate the development and delivery of comprehensive training modules. In addition, this collaboration can assist in guaranteeing that the training modules comply with regulatory standards and are current with the latest industry practices. Addressing these challenges necessitates collaborative efforts from different stakeholders. Developing a standardized certification process, capacity building programs, and collaborative initiatives can help India ensure the effective implementation of CEMS for improved environmental monitoring and compliance (CPCB, 2017; CSE, 2021; Verma, 2022; Down to Earth, 2022).

In India, there are also some challenges in adoption of USEPA/EU systems because the USEPA/EU systems have different emission standards, regulations, and technologies than India, which may not be suitable or applicable for the Indian context (CPCB, 2017). It requires extensive testing and verification of CEMS devices by independent agencies, which may not be available or affordable in India. The USEPA/EU systems may not address the specific challenges faced by the Indian industries, such as lack of awareness, technical expertise, financial resources, or operational support for CEMS implementation (CPCB, 2018; CSE, 2022).

Therefore, an indigenous certification system for CEMS in India is vital for addressing these multifaceted challenges and advancing the nation's environmental monitoring capabilities.

India urgently needs a certification system for industrial emissions monitoring devices, as there is a notable absence of a dependable and credible CEMS data quality assurance system (Down To Earth, 2022). The Indian industrial landscape is characterized by its diversity and complexity, necessitating customized and adaptable CEMS solutions to cater to the specific needs of various sectors (CPCB, 2017). Moreover, the unique climatic and environmental conditions in India can exert an influence on the performance and accuracy of CEMS devices, emphasizing the need for a localized certification system (Down To Earth, 2022; CPCB, 2018). Lastly, the 'Make in India' initiative, which promotes indigenous manufacturing and innovation, further underscores the importance of fostering homegrown CEMS manufacturers and vendors (CSE, 2022).

For this purpose, to tackle the problems related to the certification system, India developed its own CEMS certification system developed by CSIR-NPL, which is still in progress and has not been officially launched yet. The CSIR-NPL website states that they are developing a national certification scheme for CEMS in collaboration with the Ministry of Environment, Forestry, and Climate Change (MoEFCC) and the Central Pollution Control Board (CPCB). This certification system encompasses several essential components, it involves the development of national standards and protocols designed for the certification of CEMS. Additionally, a crucial aspect of this initiative is the establishment of a national CEMS testing laboratory, situated at CSIR-NPL (Council of Scientific and Industrial Research - National Physical Laboratory). To ensure the credibility and competence of the certification process, CSIR-NPL is set to gain accreditation as a certification body from the National Accreditation Board for Certification Bodies (NABCB). Finally, the scheme's practical execution will be facilitated through an online application system, encompassing testing, verification, and the subsequent issuance of certificates. This comprehensive approach aims to standardize and enhance the effectiveness of emission monitoring systems within the country (CSIR-NPL-AR, 2019-20 & 21-22).

The regulations and certification systems for CEMS can vary between countries. Some countries have established formal certification systems, while others may not. In India, the formal certification system for CEMS quality assurance is being developed by the Center for Scientific and Industrial Research National Physical Laboratory (CSIR NPL). However, CPCB mandates the installation of CEMS in certain industries. Most CEMS instruments in India are imported and come with certification from recognized agencies such as USEPA, TUV, or MCERTS. The criteria for certification of CEMS instruments are determined by agencies like USEPA, TUV, or MCERTS. Certificates issued by these agencies indicate that the instruments meet specific standards and performance specifications. USEPA, TUV and MCERTS are globally recognized certification agencies for CEMS and their certified analyzers for emissions are acknowledged for use as CEMS. It is essential to note that any modifications to certified analyzers can invalidate the certification. The CPCB guidelines in India specifically acknowledge the use of USEPA, TUV and MCERTS certified analyzers for emissions as CEMS. To ensure compliance with required standards, both domestic and foreign analyzer manufacturers must adhere to the CPCB guidelines. All manufacturers, regardless of their origin, must comply with these guidelines to ensure their instruments meet the necessary standards (CSE, 2022).

To implement CEMS effectively, it is essential to establish well-structured certification and quality assurance systems that guarantee the accuracy, reliability and comparability of data. Various countries have adopted distinct approaches to regulating CEMS installation, operation, maintenance and verification of data quality and compliance. India has faced specific challenges in adopting certification systems from these countries. The key characteristics, challenges associated with CEMS certification systems in different countries, are summarized in Table 3.

In developed countries such as EU members and USA, CEMS certification systems have been established for decades and have proved to be effective in regulating emissions and improving air quality. These countries have well-framed certification and quality assurance systems of devices, extensive testing and verification of devices by independent agencies having defined roles, responsibilities and guidelines for all the stakeholders involved in CEMS implementation. In India, on the other hand, there is no CEMS certification system that is why most of the CEMS devices are certified by certification systems of these countries and when they are function in India environment condition CEMS devices face various kinds of issues which are summarized in Table 4.

The certification systems of other countries, such as Europe and USA, may not be suitable for India, as they are based on different assumptions, standards and regulations. The Figure 14 below summarizes some of the problems that Indian industries may face and indicates why India urgently needs to develop its own CEMS certification system that is personalized to its specific needs and challenges.

The questionnaire based industrial survey revealed that most respondents certified their CEMS devices under the globally recognized TUV system. Some used USEPA certification and a few had MCERTS certification, specific to the UK. It shows the importance of certification in ensuring accurate emissions data and environmental compliance. Certification systems used by industries are shown in Figure 12.

The CPCB mandated installation of CEMS in major industries and common pollution control facilities which has limited scope in view of CEMS quality assurance until an indigenous certification system is developed. This means that there is no guarantee that the CEMS devices installed in India are accurate, reliable and suitable for the Indian conditions. The functional mechanism for to check whether the CEMS devices are properly installed, operated, maintained and calibrated is also lacking due to limited capacity of State Pollution Control Boards. This poses a serious challenge for the credibility of CEMS data and its use for regulatory and legal purposes.

4.5 Capacity Building

Industries in India face several challenges related to capacity building for CEMS. Many industries struggle to find and retain skilled personnel who can effectively operate and maintain CEMS equipment. The shortage of trained professionals can hinder the successful implementation of CEMS. The cost associated with setting up and maintaining CEMS which may enhance trained manpower in the industries for operation and maintenance is not there. Industries may face financial constraints in acquiring the necessary equipment and training their staff, which can be a significant challenge. Collecting, managing and analysing the data generated by CEMS also requires capacity building. Industries require a suitable data management systems and foundational and refresher trainings of personnel to make use of the CEMS data for decision-making to improve compliances. Industries need to carefully select reliable vendors and maintain a strong working relationship with them. Some industries may be hesitant to handle the operation and maintenance of CEMS themselves due to the associated operational risks, when dealing with sensitive and expensive equipment. Moreover, relying on third-party vendors for CEMS support may be a challenge, as the quality of vendor services may vary. There may be a lack of understanding about the benefits of CEMS and the importance of real-time monitoring. Information, awareness and communication about the advantages of CEMS would be needed to overcome this challenge. Integrating CEMS into existing industrial processes and control systems can be complex and require careful planning and expertise. Regular maintenance and calibration of CEMS equipment are crucial for accurate data collection. Industries may struggle with ensuring the ongoing upkeep of these systems (DoE, 2023).

The survey identified that methods used by industries in training and educating their staff on CEMS installation, operation and maintenance. The most commonly selected method for training staff on CEMS-related activities is in-person onsite/offsite training. A large majority of respondents indicated that they use this method, with some industries opting for both onsite and offsite training. In-person training is often considered effective for hands-on learning and is likely preferred for the technical and practical aspects of CEMS. Online courses represent another training approach chosen by a subset of respondents. While not as widely selected as in-person training, online courses offer flexibility and accessibility, making them a valuable option, particularly for remote learning. This blended approach ensures that employees have the practical skills and theoretical understanding needed to effectively work with CEMS. The survey also assesses whether industries have designated employees responsible for overseeing CEMS within their units or not. A majority of respondents confirmed that they have employees tasked with looking after CEMS within their units. Although a majority of industries have said that they have a person responsible for operation and maintenance of CEMS but the industries are yet to develop an understanding that a well capacitated and dedicated resource for CEMS operation and maintenance is required (Figure 13A-13B).

CEMS is a new technology in India and lots of industries have restricted experience in its implementation and operation. The lack of experience can result in demanding situations in which to expertise the technical components of CEMS such as choosing appropriate tracking devices, setting up facts control structures and making sure of correct data collection (CSE, 2018). Industries may additionally struggle to interpret and make use of the accrued data efficiently for emission control and compliance purposes (3ie, 2019).

To deal with these demanding situations, capacity building programs should be set up to train employees on the operation and maintenance of CEMS. These programmes can emphasize on enhancing technical intellect, information interpretation and troubleshooting abilities. Collaboration among enterprises, academic institutions and regulatory bodies can facilitate the development and distribution of extensive training modules (CSE, 2018; 3ie, 2019; MeitY, 2020).

4.6 Data Acquisition and Management System (DAMS)

Data acquisition is one of the major challenges for successful CEMS operations. This is because the CEMS must be fed with continuous data in order to detect changes in emission levels. Data must be collected from a variety of sources, including real-time and periodic readings. Quality control is also a major challenge for CEMS implementation as the data must be validated to ensure accuracy and reliability which involves careful calibration of the system to ensure the accuracy and reliability of the readings. CEMS sensors are sensitive to environmental conditions and must be regularly monitored to ensure accurate and reliable data. The data must also be validated and checked for errors and any discrepancies must be resolved before the data is used. Quality control measures can be expensive, time consuming and labor intensive which can delay the availability of data (Eisenmann et al., 2014; CPCB, 2018).

CEMS has developed a cost-effective solution to increase the frequency of data monitoring and improve enforcement of environmental regulations. In 2007, the Chinese government's Ministry of Ecology and Environment enacted a self-monitoring program that requires state controlled major pollution sources to operate with CEMS that manage more than 65% of the country's industrial pollution and are mandated to upload high-frequency CEMS data to the public online platforms (Wang et al., 2022).

Despite significant investments and data collection, the utilization of CEMS data for local environmental law enforcement has been limited due to concerns about data quality. While some studies have emerged that utilize CEMS data to evaluate pollution reduction efforts, few have explicitly discussed data quality. Technical issues such as unreliable data under irregular conditions and improper installation or calibration have been identified (Zhang & Schreifels, 2011).

Furthermore, deliberate data manipulation by firms poses a significant concern, as evidenced by studies on air quality and CEMS data. To address these challenges, a comprehensive evaluation framework encompassing three data quality criteria: completeness, accuracy and authenticity. By applying this framework to key polluting firms in Henan province, China provides policy recommendations for improving CEMS data quality and enhancing its application in environmental law enforcement (Ghanem & Zhang, 2014; Ministry of Ecology and Environment, 2017).

CEMS need to sample and analyse the flue gas stream continuously and representatively, which requires suitable sampling probes, transport lines, analysers and calibration gases. The sampling and analysis methods should be compatible with the type, concentration and variability of the pollutants and the flue gas conditions. The sampling and analysis techniques should also meet the performance specifications and quality assurance requirements of the relevant standards and regulations. CEMS need to undergo regular quality control activities to ensure that they are operating properly and producing valid data. These activities include calibration checks, system audits, preventive maintenance, repair programs, spare parts inventory and record keeping. The frequency and procedures of these activities should follow the guidelines and protocols of the applicable standards and regulations (US EPA, 2022).

CEMS need to have a DAMS that collects, processes, stores and reports the emission data from the analysers and other sensors. The DAMS should be capable of handling large volumes of data, performing data validation and correction, calculating emission rates and averages, generating reports and alarms, and transmitting data to external systems. The DAMS should also be secure, reliable, user-friendly and compliant with the data format and reporting requirements of the regulatory authorities (CPCB, 2017; FE, 2023).

However, CEMS QA/QC are involving various technical, operational and regulatory challenges that need to be addressed properly to ensure the reliability and accuracy of the CEMS data in India.

Several critical issues exist in the context of CEMS in India. Primarily, due to absence of a certification system for CEMS equipment and service providers, the reliability and accuracy of the data generated is undermined. Secondly, the lack of a standardized protocol for calibration, maintenance and audit of CEMS contributes to data inconsistency and incomparability. Furthermore, the absence of clear guidance on how to apply international standards such as EN 14181 and EN 16442 for Quality Assurance/Quality Control (QA/QC) of CEMS creates confusion and ambiguity among stakeholders. Another concern is the lack of a robust data management system for CEMS data, which hinders the verification, validation and reporting of this critical information. Lastly, inadequate awareness and capacity among industry and regulatory bodies regarding the benefits and requirements of CEMS may impair the effective implementation and enforcement of CEMS practices in India (CSE, 2022; Kanchan, 2023).

In India, using systems to collect and manage data from emission monitoring systems (CEMS) comes with several challenges. These include making sure that the data works well with different systems, keeping the data safe and dealing with issues related to how the data is sent and shared. One of the major issues is maintaining the frequency of data transmission, as industries often fail to send data at the minimum desired level of 85% of their operation time. Data quality is also very challenging, as there are often missing or null values that arrive at the server. Data manipulation is another problem, as some instances have been reported by CBCB. Data science techniques can be deployed to identify and prevent such fraudulent or inaccurate data. Development of data science cells or data analytics teams is essential to properly analyse, monitor and validate data on a regular basis. Development of algorithms that can detect data disruption is also needed (DoE, 2023).

The survey revealed that how industries utilize CEMS data to enhance their operations. The majority of industries focus on optimizing emission control parameters, while many also use the data to identify and correct emission deviations and ensure continuous compliance with environmental regulations. A notable portion of respondents adopted a comprehensive approach that incorporates all of these strategies, highlighting the adaptability of CEMS data in improving environmental performance and regulatory compliance.

The survey investigated into the methods employed by organizations to analyse CEMS data in their industrial operations, revealing that the most dominant approach involves using software or systems provided by CEMS vendors or providers. Many industries rely on these tools for effective data analysis. A significant number of respondents also indicated utilizing a combination of methods, implying a mix of vendor-provided software and additional tools or approaches. Additionally, a few organizations mentioned their use of self-regulation and in-house data analysis methods, representing the diversity of strategies used to extract valuable insights from emissions data.

The survey meant to discover how industries secure the quality and reliability of their CEMS data and the findings reveal a multi-faceted approach. Periodic calibration, involving regular adjustments and verification of instrument accuracy, is a primary method. Additionally, many organizations state the importance of adhering to standard operating procedures and quality assurance protocols, which establish guidelines for data collection, maintenance and quality control. Notably, a significant number of respondents adopt a comprehensive strategy, selecting "All of the above," which suggests a combination of periodic calibration, adherence to SOPs and potentially other quality assurance measures.

The challenges faced by industries when it comes to utilizing CEMS data are multiple and include various aspects. One of the most prominent challenges is the lack of effective data interpretation or communication. This indicates that while data might be collected, industries struggle to derive meaningful insights or effectively communicate findings. Ensuring that data from CEMS systems seamlessly integrates into existing data infrastructure is another challenge. Compatibility issues can hinder the utilization of CEMS data. It's notable that many respondents selected "All of the above," indicating that they face a combination of these challenges in their industry. These challenges highlight the importance of not only collecting CEMS data but also investing in the necessary resources, expertise and technology to extract value from this data effectively (14A-14D).

The survey provides valuable insights into how industries report and share their CEMS data with regulatory authorities. The majority of respondents reported that they utilize a data acquisition and handling system to report their CEMS data to the relevant authorities. This system likely serves as a sophisticated digital infrastructure for collecting, storing and transmitting emissions data. A substantial number of respondents also reported using both data acquisition and handling system as well as an offline approach, specifically through manual reports. This suggests that some organizations also prepare physical or electronic reports that contain CEMS data, which are submitted separately to the regulatory authorities.

Based on the responses to the survey question regarding problems related to the server of the Central Pollution Control Board (CPCB), it is evident that some industries have faced issues, while others have not. Out of the total respondents, 18% of industries indicated that they have faced problems related to the CPCB server, while the remaining 82% reported no such issues. The types of problems reported by the minority of industries that faced server-related problems are primarily related to connectivity and network issues. Some respondents mentioned connectivity problems, which could imply difficulties in establishing a stable connection with the CPCB server. A subset of respondents specifically mentioned network-related problems, which could indicate that issues arise due to poor network conditions or occasional data transmission failures. It's worth noting that a few respondents provided additional context, mentioning that these issues occur "sometimes".

For the majority of industries that reported no server-related problems, it suggests that they have experienced a smooth and reliable interaction with the CPCB server. This is a positive sign, as it indicates the server's reliability and performance for a significant portion of respondents. The nature of the problems appears to be primarily related to connectivity and network challenges, which may require further attention and improvement to ensure seamless data transmission and communication with the CPCB server (15A-15B).

4.7 Challenges in CEMS Ecosystem

The questionnaire-based survey and stakeholder consultation with CEMS experts under this research revealed that several key players are involved in the CEMS market in India and their roles in the adoption and monitoring system of CEMS. They are pioneers in technology and environmental responsibility, actively supporting pollution reduction and sustainable industry initiatives. However, despite the advancements, implementing CEMS in India faces multiple challenges. These issues of CEMS ecosystem are detailed in the following Figure 16.

Successful implementation of CEMS in India relies on the collective efforts of key players, such as industries, regulators, vendors, service providers, manufacturers, researchers, etc., each fulfilling vital roles within the CEMS ecosystem. The structured role of these key players, their interconnections and the prevalent challenges they face when seeking to establish CEMS at ground level are as follows:

Industries encompass a broad spectrum of entities, from large corporations to small and medium-sized enterprises, constituting the primary users of CEMS. These organizations play a pivotal role in the deployment of CEMS to effectively monitor and regulate emissions. Regulators such as Central Pollution Control Board (CPCB) and State Pollution Control Boards (SPCBs) serve as regulatory authorities responsible for formulating, enforcing and overseeing regulations related to emissions monitoring. They are the custodians of standards and guidelines for the seamless implementation of CEMS. Certification Bodies are charged with the critical task of evaluating and certifying the performance and accuracy of CEMS equipment. In the Indian context, the National Physical Laboratory (NPL) is actively engaged in developing a certification system.

Manufacturers and suppliers of CEMS equipment and technology are the bedrock of CEMS infrastructure, supplying the necessary hardware and software for the accurate monitoring of emissions. Their role is instrumental in ensuring the reliability and precision of the monitoring process. Service providers offer services such as installation, maintenance and calibration of CEMS. Researchers and academic institutions are engaged in the advancement of knowledge and best practices in emissions monitoring. They contribute to research, training and the dissemination of expertise in the field.

The various key players within the CEMS ecosystem are interlinked, establishing a collaborative network essential for the successful implementation of CEMS. Industrial organizations depend on vendors for the procurement of CEMS equipment and may enlist service providers for installation and maintenance. Government agencies collaborate with certification bodies to uphold compliance to ensure that emissions monitoring adheres to established standards and guidelines. Researchers provide the knowledge and expertise crucial for effective CEMS implementation and continuous improvement. Lack of Certification of CEMS in India is a major challenge regarding the quality and reliability of monitoring equipment.

High Initial upfront costs involved in CEMS implementation, installation and training poses a substantial barrier, particularly for smaller industries. Lack of Standardization of uniform standards for CEMS devices in India introduces variations in emission limits, measurement methods and sampling techniques creating challenges in achieving compliance.

Infrastructure limitations associated with consistent power supply and internet connectivity can impair CEMS operation, especially in remote or underdeveloped areas. Regulatory loopholes and non-compliance of some industries may result in non-compliance with emission standards.

Similarly, the lack in the availability of accredited laboratories is another challenge in CEMS ecosystem. Accredited laboratories play a key role in the CEMS adoption by providing the necessary calibration, validation and certification services for the monitoring equipment. Their role is crucial in ensuring the accuracy, reliability and compliance of CEMS data. This shortage of accredited labs poses a challenge to the effectiveness of CEMS in ensuring environmental compliance and data accuracy. It implies that, without access to accredited labs, industries may face hurdles in obtaining the necessary certifications and validations for their CEMS equipment.

The collaborative efforts of the key players within the CEMS ecosystem in India, including industrial organizations, government agencies, certification bodies, technology providers, service providers, research and academic institutions are instrumental in addressing the challenges and hurdles faced in the effective implementation of CEMS (DoE, 2023).

4.8 Compliance

According to regulatory guidelines, CEMS is defined as a comprehensive collection of equipment necessary for the determination of gas or particulate matter concentration or emission rate. This is achieved through the utilization of pollutant analyzer measurements along with a conversion equation, graph or computer program that produces results in units aligned with the relevant emission limitation or standard (CPCB, 2018). To ensure effective monitoring, regulatory agencies now rely on continuous monitoring techniques, making it obligatory for emission sources to self-report instances where permissible limits are exceeded. The responsibility lies with the owner or operator of the facility to ensure that each CEMS is capable of not only accurately measuring but also recording and reporting data. In cases where a Source Compliance Test is not required, CEMS must be installed, operational and certified within 180 days from the stipulated requirement (CSE, 2022). Compliance assurance policies play a crucial role in establishing standardized criteria for evaluating monetary penalties in instances of surpassing emission standards and data availability requirements which in turn enable the monitoring of emissions and demonstration of compliance with emissions standards or operational criteria (US EPA, 2020).

High-resolution emission inventories are crucial for evaluating air quality and health effects. In a study on power plants in Jiangsu, China, an hourly NOx emission inventory was established using a CEMS network. The method coupled unit-level fuel consumption and emission factors to reduce uncertainties. The accuracy of this method was compared to three other bottom-up inventories and the results showed higher accuracies for the CEMS (Improved) method compared to BASE EIs and CEMS (Traditional). The total NOx emissions from power plants in Jiangsu in 2018 were 43,701 tons with 53% contributed by the southern Jiangsu area and super units (>1000 MW) having the largest emissions shares of 70% (Shahbazi et al., 2020; Gu et al., 2022). To ensure the accuracy and reliability of CEMS data, there are specifications, certification tests and quality assurance procedures outlined in EPA regulations. These measures help to maintain the integrity of the monitoring system and ensure compliance with regulatory requirements (CFR, 2023).

Assessing and ensuring compliance with emission limitations and standards is a crucial role played by CEMS. The provision of real-time data on gas or particulate matter emissions enables effective monitoring and regulatory compliance.

5 Opportunities

5.1 Advancements and Innovations in CEMS Technology

Advancement and innovation in (CEMS) technology have become a focal point for manufacturers aiming to meet the demands of end users. These advanced systems integrate the technologies, such as smart sensors, lasers and real-time monitoring systems, resulting in enhanced reliability, accuracy, cost-effectiveness and ease of monitoring for industrial measurement equipment. The software segment, which includes data analysis and reporting, is gaining popularity while the service segment encompasses calibration, installation and maintenance services. Among the various industries adopting CEMS technology, the power generation sector leads the global market (FMI, 2023).

In the past, emission systems relied on discrete hardware and costly sensors for tracking emissions data. These hardware-dependent CEMS were dispersed throughout all the industries (Kamas & Keeler, 1995). However, Predictive Emission Monitoring Systems (PEMS), employing non-linear hybrid predictive models, have emerged as a cost-effective alternative to CEMS, meeting regulatory requirements and exhibiting precision and dependability. These predictive models assimilate various inputs, including fuel flows, fuel quality, air flow, process oxygen and temperature and humidity measurements to optimize performance while minimizing fuel emissions (Haiming & Guiji, 2008).

For large gas turbines, PEMS have proven effective in predicting NOx emissions, with the accuracy, reliability and robustness of PEMS depending on the quality of emissions data used for their development. First principle and feed forward neural network models have shown superior performance compared to statistical hybrid models. Ensuring comprehensive and representative CEMS data, conducting sensitivity testing during model validation, adhering to USEPA standards for its calibration, avoiding changes in its instrument settings during PEMS development and conducting pre study audits of data quality are recommended practices. It is also a cost-effective and compliant solution for emissions monitoring, utilizing algorithm-based techniques instead of hardware-based sensors. These digital models incorporate specialized original equipment manufacturer (OEM) knowledge, enabling operators to achieve substantial reductions in capital expenditure (CAPEX) and operational expenditure (OPEX) associated with emissions measurement processes (Sadois et al., 2014). Various companies specialize in the development of CEMS with advanced technologies like ECOTECH utilizes extractive dilution probe technology to measure high concentrations of gases emitted from chimneys or stacks, providing accurate emission level data (ECOTECH, 2017). ENVEA offers a comprehensive CEMS solution including gas and dust analyzers, sampling systems, data acquisition systems and software to assist clients in achieving environmental compliance (ENVEA, 2017). FUJI Electric France's CEM incorporates advanced NDIR gas analyzers, an oxygen analyzer and a well-engineered sample probe and gas conditioning system, ensuring compliance with environmental regulations (FUJI Electric, 2023). Recent research has been dedicated to advancing CEMS technology in terms of accuracy, reliability and sensor development to enhance the effectiveness of CEMS in monitoring and mitigating air pollution as well as protecting public health and the environment. CEMS facilitate the identification of potential pollution sources, enable timely corrective actions and contribute to the development of effective pollution control strategies. With ongoing advancements and research, CEMS are poised to play an increasingly vital role in environmental monitoring and safeguarding human well-being (Wang et al., 2023).

5.2 Strengthening Policy regulations

Although CPCB has mandated CEMS installation in certain industries through a regulation but a policy to support CEMS adoption that deals with the whole ecosystem is lacking in India. To implement CEMS properly in India, a clear and comprehensive policy framework addressing the challenges in complete value chain is required. This policy should be developed with the participation and cooperation of various stakeholders and address the technical, legal and financial aspects of CEMS. It is important that all industrial units (17-categories of industries as per CPCB guideline), especially those within designated industrial clusters, must install duly certified CEMS and operate and maintain CEMS as per the guidelines through a completely transparency in data sharing. This requirement ensures that emissions are accurately monitored and reported, promoting environmental responsibility and compliance.

To further enhance the effectiveness of CEMS, the establishment of a domestic certification system is crucial. This certification system should be recognized by regulatory authorities and ensure that CEMS data adheres to the highest standards of accuracy and reliability.

After certification protocols have been developed by CSIR-NPL, a state of the science laboratory is needed for product certification at national level. Each industrial cluster should have a dedicated CEMS laboratory equipped to calibrate the CEMS equipment. Each dedicated CEMS laboratory for calibration should be NABL accredited (preferably empanelled with NPL). This laboratory infrastructure will facilitate the accuracy and reliability of emissions data, essential for real time monitoring of the stacks and will pave the way for its use for regulatory compliance.

The implementation gaps identified in this study have been addressed by the suggestions and solutions proposed by the stakeholder consultation with CEMS experts. To overcome or fill the gaps for the CEMS implementation, our research suggested solutions that are presented in Figure 17.

5.2.1 Skill Development

The operation and maintenance of CEMS require specialized skills. To address this need, we propose the development of 'Green Skilled Workforce' linked with Skill India Mission.

The Government of India (GOI) launched the Skill India Mission, a skill development initiative scheme that aims to enable Indian youth to take up industry-relevant skill training that will help them in securing a better livelihood. Under this mission, the Pradhan Mantri Kaushal Vikas Yojana (PMKVY) is a flagship scheme that provides grants for training and certification of various personnel. A module can be developed for CEMS training which can be registered under the PMKVY scheme to avail the grant (PMKVY, 2023). This can help to fill the gaps in proper management of CEMS operation and maintenance with the help of the following steps:

- States will conduct their skill gap assessment for CEMS with the help of professional agencies and academic institutions. They can also seek technical support from National Skill Development Corporation (NSDC) and Sector Skill Council (SSCs) in designing this gap assessment.
- Then, Sector Skill Council will design a standard curriculum and resource material for CEMS training that is aligned with the National Skills Qualification Framework (NSQF), defining the eligibility of the individuals undergoing the training. The following are the suggested criteria to be considered for eligibility and course certification for CEMS by SSCs for the individuals undergoing the CEMS training:
- SSCs are mandated to conduct training of trainers (ToTs) for certification of trainers. Any established Training Institutes of repute (Govt. Institutions/Govt. Universities/Industry partners), identified by SSC to conduct ToT/ToA may get an exemption from accreditation and affiliation process, as per discretion of the SSC.
- The training experts of CEMS or training provider (TP) will register themselves on the Skill Management & Accreditation of Training Centre (SMART) portal and submit the proposal for CEMS training under the Short-Term Training (STT) component of PMKVY 4.0 scheme and provide their details of training centre, trainers, infrastructure, equipment, target beneficiaries and expected outcomes. The proposal will be evaluated by NSDC or state skill development Mission (SSDM), depending on whether the trainer is applying for the Centrally Sponsored Centrally Managed (CSCM) or the Centrally Sponsored State Managed (CSSM) component of the scheme. Provide details about your organization, training infrastructure, trainers, courses, etc. and pay a registration fee. They will also have to undergo a due diligence process by

National Skill Development Corporation NSDC or SSDM to verify your eligibility and quality standards.

- Then the proposal for training module of CEMS will be approved by Ministry of Skill Development and Entrepreneurship (MSDE) and the trainer will be allocated targets/ funds for CEMS training under PMKVY 4.0 scheme.
- Trainers will conduct the CEMS training as per the approved curriculum and training schedule by MSDE. The responsibility of assessment and certification of the candidate lies with SSCs and will be facilitated by NSDC.
- Later the trainers will submit the claims and reports to NSDC, as per the prescribed format. They need to provide evidence of the training delivery, assessment, certification, placement and post-placement outcomes. They will receive the grant as per the fund disbursement mechanism of the scheme, based on the verification of claims and reports by the Project Management Agency (PMA) (PMKVY, 2023; MSDE, 2023).

5.2.2 Innovative Financing Models

To overcome the financial gaps related to capital cost, operation, maintenance and calibration etc. firstly the capital cost of CEMS can be reduced by taking advantage of economy of scale. The economy of scale refers back to the cost benefits that arise while the manufacturing of a product or service increases. In the case of CEMS, the cost per unit can be reduced by growing the number of devices produced. This may be accomplished by encouraging greater industries to adopt CEMS that can help to grow the demand for emission tracking equipment and cause lower costs. Another way to make CEMS more feasible is to keep in mind the total cost of the ownership. The overall cost of ownership consists of the preliminary value of buying and installing a tracking device, as well as the ongoing expenses of operation, calibration and maintenance including the cost incurred for manually tracking the emissions and that for non-compliances. The cost incurred in non-compliances may include losses owing to closure of the production, legal cost etc. that arises out of enforcements by the regulators for non-compliances. The industries could take informed decisions about maximum cost-effective monitoring answers. Innovative financing models can also help to make CEMS low priced e.g. - Public-Private Partnerships (PPPs) can be set up to share the cost of imposing CEMS. The government can offer incentives to industries that adopt CEMS, together with tax credits or subsidies. The implementation of CEMS in India has been tough because of various financial factors. However, taking advantage of the financial model of economy of scale, considering the total cost of ownership and exploring innovative financing models, the cost of CEMS may be decreased (3ie, 2020; CSE, 2016; Mongabay India, 2018).

Lowering the cost of CEMS by demand aggregation is another strategy that can help reduce the cost of installing and operating CEMS for small scale industries. It involves pooling the demand and resources of multiple industries that want to invest in CEMS and leveraging economies of scale to negotiate better prices and terms with the suppliers and service providers of CEMS technology. It can also help create a network of industries that can share best practices and learn from each other's experiences with CEMS. In addition to this, providing capital subsidy will also enable the development of a platform for providing financial incentives. Some examples of cost lowering by demand aggregation are:

The Gujarat Pollution Control Board (GPCB) has initiated a pilot project to install CEMS in 55 small and medium enterprises (SMEs) in the chemical sector in Vapi, Gujarat. The project involves creating a consortium of SMEs that can collectively procure, install and operate CEMS with the help of a third-party agency (GPCB, 2023).

Centre for Science and Environment (CSE) has launched a stakeholder initiative to facilitate the adoption of CEMS in India. The initiative provides a common platform for the industries, regulators, device manufacturers and service providers to share their experience and discuss on the challenges and solutions for CEMS installation and operation. The initiative also helps in creating demand aggregation among the industries that want to invest in CEMS and connecting them with the suppliers and service providers of CEMS technology (CSE, 2017).

Policy interventions like the UP Industrial Investment and Employment Promotion Policy (UPIIEPP) 2022 and the Green Credit Programme (GCP) could offer subsidies and incentives to support expenditures on CEMS in Greenfield projects. The UP Industrial Investment and Employment Promotion Policy (UPIIEP) 2022, launched by the Uttar Pradesh Government, aims to make the state a one-trillion-dollar economy by 2030. It is an umbrella policy that provides a strategic framework for the sustainable industrial development of the state over the next five years. The policy aims to attract investments, create employment opportunities and promote sustainable and inclusive growth. The policy also provides for incentives on investment in installation plant for pollution control measures, including disposal of emission or gaseous hazardous waste as eligible investment under Plant & Machinery head of Capital Investment. Therefore, UPIIEP, 2022 could provide support for installation of CEMS by extending some of these incentives and subsidies to the industries that invest in CEMS technology and demonstrate their environmental performance and compliance (UPIIEPP, 2022).

The Green Credit Programme can be leveraged to recover capital expenditure and operational costs for these industries. It is a market-based mechanism that aims to incentivize voluntary environmental actions by various stakeholders, including industries. The program covers eight sectors, including air pollution reduction and allows participants to earn tradable credits for compliance with pollutant emission standards. Green Credits will be made available for trading on a domestic market platform and activities generating Green Credits may also receive Carbon Credits (GCP, 2023).

In addition to existing practices, the installation of CEMS can be considered for base lining the emissions/air pollution and it's tracking after the best practices have been adopted by the industry so that authentic and validated Green Credits may be generated. Thus, CEMS may be utilized not only to generate the Green Credits but also to validate it. Our research has proposed specific methodologies for CEMS, as depicted in Figure 20.

5.2.3 Certification system & Quality Control

To tackle the problems related to the certification system, India needs to establish its own CEMS certification system which is being developed by Council of Scientific and Industrial Research-National Physical Laboratory (CSIR-NPL). The CSIR-NPL website states that they are developing a national certification scheme for CEMS in collaboration with the Ministry of Environment, Forest and Climate Change (MoEFCC) and the Central Pollution Control Board (CPCB). This certification system includes several essential components including the development of national standards and protocols designed for the certification of CEMS. Additionally, a crucial aspect of this initiative is the establishment of a national CEMS testing laboratory, situated at CSIR-NPL. To ensure the credibility and competence of the certification process, CSIR-NPL is set to gain accreditation as a certification body from the National Accreditation Board for Certification Bodies (NABCB). Finally, the scheme's practical execution will be facilitated through an online application system, including testing, verification and the subsequent issuance of certificates. This comprehensive approach aims to standardize and enhance the effectiveness of emission monitoring systems within the country (CSIR-NPL-AR, 2019-20 & 21-22).

CSIR-NPL performs CEMS certification by evaluating the design, specifications and features of specific CEMS devices or models. It tests them against technical requirements to ensure their functionality, accuracy, durability, safety and compatibility. CSIR-NPL can also certify CEMS technology by examining their measurement principles and methods and providing certificates or reports.

Having developed the indigenous certification system for CEMS by CSIR-NPL, the CEMS may be brought under the ambit of The Bureau of Indian Standard Act, 2016 in order to ensure its standardization, conformity assessment and quality assurance. BIS should mandate the device certification of CEMS and issue a certificate or mark of conformity to the products that comply with the relevant standards (BIS, 2023). The following steps describe how to obtain the BIS Registration under the BIS compulsory registration scheme (CRS) (Figure 21).

Also, the adoption of CEMS in India is increasing, hence it is suggested that all the CEMS devices whether they are imported or indigenously developed should undergo mandatory product certification under BIS Act, 2016.

Until the above CEMS certification system is developed by CSIR-NPL, our research also proposed a CEMS product certification as per CSE.

For product certification of CEMS device, manufacturer or client download the application from SPCBs site and submit the application for product certification then a certification committee is essential for CEMS certification system, as it will oversee all the certification processes for any CEMS device. The committee should consist of independent experts who can provide technical support for certification process. The committee also obtain international accreditation and follow established standards such as ISO/ IEC 17025 to ensure international traceability.

A testing facility is required to perform the tests directed by the certification committee. The testing facility should be accredited by an authorized body and comply with the standards of ISO 17065 and ISO 17025. The testing facility should have the equipment and capability to test and calibrate different types of CEMS devices, both in the laboratory and in the field. The testing facility should also be able to conduct field testing on-site for three months, as per the international norms, NPL should designate some laboratories as testing facilities. The testing facility should have the basic infrastructure and skilled manpower to perform the tasks related to CEMS.

To certify the CEMS, performance standards for different tests are required, which can be based on the existing ones in Europe. These standards have been followed by many countries for decades and ensure the reliability of the CEMS. The testing facility should also account for the environmental conditions that may affect the test results. A test report should be prepared and submitted to the certification committee for review after completing the tests after that certification issue or rejected based on the decision on certification committee (CSE, 2022).

Until the indigenous certification system is in place, the certification process proposed by CSE may be employed and pollution control boards, regulatory bodies, etc. can observe the Real-time data obtained from the industry emissions using CEMS online. In the case of exceeding emissions limits, on-ground inspections can be conducted only for units or industries that consistently exceed these limits. This will save time, resources and energy for regulatory agencies and enhance compliance. This data can be used for initial level of intelligence and insights which means, while it may not be used as real evidence in legal matters, it can serve as a foundational source of information and knowledge for industries and authorities to understand emission patterns, identify potential issues and take proactive measures to improve environmental compliance and performance.

5.3 Economy of Scale and Cost Considerations

In India, the implementation of CEMS has been tough because of various factors, together with excessive fee, loss of infrastructure and absence of certification structures. However, there are approaches to deal with these demanding situations and make CEMS more feasible.

One manner to reduce the value of CEMS is to take advantage of the financial system of scale. The economy of scale refers back to the fee benefits that arise while the manufacturing of a product or service increases. In the case of CEMS, the fee per unit can be reduced by growing the variety of devices produced. This may be accomplished by encouraging greater industries to adopt CEMS that can help to grow the demand for tracking equipment and cause lower costs. Another way to make CEMS more feasible is to keep in mind the total price of ownership. The overall fee of possession consists of the preliminary value of buying and installing a tracking device, as well as the ongoing expenses of preservation, calibration and statistics management. By thinking about the entire price of ownership, industries could make knowledgeable decisions about maximum cost-effective monitoring answers. Innovative financing models can also help to make CEMS low priced e.g. - public-non-public partnerships can be set up to share the cost of imposing CEMS. The government can offer economic incentives to industries that adopt CEMS, together with tax credits or subsidies. The implementation of CEMS in India has been tough because of various financial factors. However, taking advantage of the financial system of scale, thinking about the whole cost of ownership and exploring innovative financing models, the cost of CEMS may be decreased (3ie, 2020; CSE, 2016; Mongabay India, 2018). The cost of CEMS can be a considerable barrier for industries in India. The preliminary funding required for getting and putting in monitoring devices as well as the ongoing charges of maintenance, calibration and records management are quite high. Small and medium-sized organizations, specifically may struggle to allocate the essential economic sources for CEMS implementation (3ie, 2019).

We can lower the cost of CEMS by demand aggregation is a strategy that can help reduce the cost of installing and operating CEMS for small scale industries. It involves pooling the demand and resources of multiple industries that want to invest in CEMS and leveraging economies of scale to negotiate better prices and terms with the suppliers and service providers of CEMS technology. It can also help create a network of industries that can share best practices and learn from each other's experiences with CEMS. Some examples of cost lowering by demand aggregation are:

The Gujarat Pollution Control Board (GPCB) has initiated a pilot project to install CEMS in 55 small and medium enterprises (SMEs) in the chemical sector in Vapi, Gujarat. The project involves creating a consortium of SMEs that can collectively procure, install and operate CEMS with the help of a third-party agency (GPCB, 2023).

Centre for Science and Environment (CSE) has launched a stakeholder initiative to facilitate the adoption of CEMS in India. The initiative provides a common platform for the industries, regulators, device manufacturers and service providers to share their experience and discuss on the challenges and solutions for CEMS installation and operation. The initiative also helps in creating demand aggregation among the industries that want to invest in CEMS and connecting them with the suppliers and service providers of CEMS technology (CSE, 2017).

5.4 Capacity Building

Capacity building on CEMS involves enhancing the knowledge, skills and capabilities of individuals, organizations or regulatory bodies to effectively understand, implement and manage CEMS for environmental monitoring and compliance purposes.

The Environmental Training Unit (ETU) of the Central Pollution Control Board, Delhi organized an online training programme of three days through ESCI Hyderabad. The detail of training programme is shown below in Table 6A:

Apart from the training conducted by CPCB, most of the training and capacity building programs for CEMS in India were conducted by CSE India. Following is the list of the training programs conducted by CSE India as shown in Table 6B:

Training for CEMS operation is essential to ensure the quality and reliability of emissions monitoring. However, India does not currently have any official training system for CEMS operation, unlike the UK and the USA, which have established systems for training and certifying individuals who carry out emissions monitoring. These systems cover CEMS and additional areas of stack testing, such as manual monitoring, wet chemical methods, data handling and health and safety on site.

In the UK, the MCERTS scheme established by UK Environment Agency (UKEA) covers all areas of emission and effluent monitoring. This training is commonly delivered via the UKEA or through the UK Source Testing Association (STA). The courses for CEMS operation include CEMS operation, data management and competence certification for personnel. Individuals and organisations can obtain certification at different levels of competency. Certification can be obtained both at the individual level and the organisation level. Individuals can advance through three levels of competency from trainee to team leader.

Similarly, in the USA, the US Source Evaluation Society (SES) has established the Qualified Source Testing Individual (QSTI) and Qualified Source Testing Observer (QSTO) certification scheme to demonstrate that qualified staff have the knowledge and skills required to apply source testing methods correctly. The qualification is voluntary but is approved by the USEPA (Kanchan S.K., 2023).

In India, there are only a few generic training courses on CEMS, which have been organised by the CPCB and some independent organisations such as CSE. However, there is no CEMS related training provided by the UPPCB or any other organisation in Uttar Pradesh. This is not sufficient to ensure that CEMS are operated correctly and that the data are valid for compliance reporting. This lack of training and capacity building will result in poor data quality and implementation challenges.

To address this gap, the International Centre for sustainable Carbon (ICSC) delivered four training workshops in India in 2022 under a US Department of State funded programme. However, these materials need to be updated and maintained by Indian stakeholders. Therefore, the ICSC has established CEMS-India, a stakeholder working group that focuses on advancing CEMS training and use in India (Kanchan, 2023).

Recently, DoEF&CC, GoUP has proposed Uttar Pradesh Clean Air Management Project under the World Bank Program for Air shed management in Uttar Pradesh. The Apex Institute will act as a central hub for the UP Clean Air Management Project. It will provide crucial support to the 15 Knowledge Centres located in various educational institutions across the state. The Apex Institute will offer comprehensive capacity building support to the Knowledge centres. Since, there is a lack of institutions that provide CEMS related training in UP, it will also facilitate the development of training programs, workshops and refresher courses related to air quality monitoring devices including CEMS to enhance the knowledge and skills of professionals engaged in air quality management. These programs will be delivered through online and offline platforms.

To address the gap of trained personnel, we propose the following solution. The number of persons required for the installation and data transfer of CEMS in an industry may vary depending on various factors, such as the type and size of the industry, the number and location of the emission sources, the complexity and compatibility of the CEMS equipment and software and the availability and expertise of the staff. However, based on the guidelines for CEMS installation and operation, the following persons are required for CEMS, which are as follows:

- For installation, operation and maintenance of CEMS, at least one person is required from the CEMS vendor who will ensure proper installation and commissioning of the CEMS device.
- For technology selection and proper monitoring, at least one person is required from the industry who is responsible for monitoring and maintaining the data acquisition system (DAS), which is a computer with internet connection that collects and stores the CEMS data.
- To calibrate CEMS as a third-party, trained and dedicated personnel are also needed, who have the skills and knowledge of calibration procedures for CEMS.

Therefore, in total, at least three persons are required from installation to data transfer and calibration from each point of CEMS process in an industry. However, this number may vary depending on the specific requirements and conditions of each industry.

The number of trained personnel to maintain CEMS depends on various factors, such as the type and number of CEMS devices, the frequency and method of calibration, the level of automation, and the availability of technical support. A guideline by the CPCB in August 2018 suggested that each industry should have at least one trained person for each CEMS device installed. However, this may not be sufficient or feasible in practice, as CEMS devices may require regular maintenance, troubleshooting, and verification by external agencies. Therefore, the actual number of trained personnel to maintain CEMS may vary across industries and regions (CPCB, 2018; Greenstone et al., 2020).

Furthermore, it was found evident that installation, operation and maintenance of CEMS require careful planning and preparation, as there are several parameters that need to be checked before implementation. These technical parameters for implementation of CEMS are well explained in CPCB guidelines 2018, but industries find it difficult to follow these guidelines meticulously due to lack of understanding of the CEMS guidelines of CPCB. Hence, it is recommended that CPCB should come out with a capacity building program of CEMS guidelines for industrial stakeholders for proper implementation of CEMS in industries.

After discussing with various stakeholders and CEMS experts, it was identified that the workforce or trained personnel required for CEMS processes is only 10-20% of what is needed for their proper installation, operation and maintenance in India. This indicates a large gap in this area, so we must train these people and build their capacity to fill this gap and ensure proper implementation of CEMS in India. For this, the government's Skill India programmes should include a training and capacity building module for CEMS in India, which would provide proper training and management courses for CEMS. This way, the gap can be filled and the requirement of trained personnel can be met for CEMS implementation in India. Some of the key points for training the person and building their capacity to address the gap of capacity building for proper implementation of CEMS are shown in Figure 23.

5.5 Data Acquisition and Management System

To address the challenges of data management from CEMS, our research proposed to establish a Data Acquisition and Management System (DAMS) for proper handling of CEMS data, s shown in Figure 24.

5.6 Internal Monitoring Mechanism

The UP Clean Air Management Plan, developed by the Department of Environment (DoE), aims to combat air pollution in Uttar Pradesh. It involves establishing an Apex Institute at IIT Kanpur and 15 Knowledge Centres within educational institutions across the state. The Apex Institute will coordinate and support the activities of the Knowledge Centres, collectively strengthening efforts against air pollution. It will provide capacity-building support through online and offline training programs, including stack monitoring, emission inventory and CEMS training. The Knowledge Centres will offer well-equipped labs, contribute to a skilled workforce, support the CEMS ecosystem, establish an internal monitoring mechanism, conduct source apportionment and impact assessments and also play a crucial role in understanding and mitigating the effects of air pollution in Uttar Pradesh. Every industrial cluster has a Common Facility Centre in which the Industrial Development Authority will provide free space for establishment of CEMS laboratory. This will encourage the creation of CEMS labs in every industrial cluster through a public-private partnership model. In this model, the industrial cluster offers space for labs and the government offers financial support in the form of a Capital Subsidy to establish

CEMS labs. The government of Uttar Pradesh (UP) is offering a 10% subsidy for establishing CEMS labs as part of the UP Clean Air Management Plan (UPCAMP Draft DPR, 2023).

To establish an internal monitoring mechanism for air pollution, Project propose a CEMS ecosystem in the industrial areas. The key components of this system are shown in Figure 25.

By incorporating these additional measures, we can create a more comprehensive and multi-faceted internal monitoring mechanism, effectively addressing various sources of air pollution within the industrial area and facilitating timely corrective actions.

5.7 Implementation Strategy for CEMS in India

There are some technical aspects of CEMS that need to be documented for their implementation and to assist the industry in selecting the right instruments and ensuring their long-term operation and performance evaluation. The technical working of CEMS is summarized below in Figure 26.

5.8 Service and Support

CEMS services and support face challenges in India due to various factors. The rules governing CEMS set by CPCB are complicated and occasionally lack clarity. Complying with the regulations can become challenging for industries. Service providers may also experience confusion and uncertainty. The regulations lack specific details on the calibration and maintenance requirements for CEMS. The statement can be understood differently by different industries and service providers (CPCB, 2018).

The expertise to install, operate and maintain CEMS is in short supply in India. Finding qualified personnel to support their CEMS systems can be challenging for industries. CEMS personnel certification program is not offered by the CPCB. It is challenging to guarantee that the personnel operating CEMS systems possess the required skills and knowledge. Small and medium-sized enterprises often face high costs for CEMS. Implementation can be challenging for certain industries due to this factor. The CPCB does not offer financial assistance to industries for offsetting the cost of CEMS. Affording the installation and operation of CEMS systems can be challenging for certain industries (CSE, 2022).

Effective implementation and operation of CEMS systems in India can be significantly affected by the challenges in service and support. With appropriate focus and investment in resolving these difficulties, it is possible to address them and secure the seamless operation of CEMS in the country. The complexities involved can pose challenges for industries in meeting emission regulations. They can also result in accuracy and reliability problems with CEMS data.

The Directorate of Environment (DoE), Gomti Nagar, Lucknow, conducted a questionnaire-based survey to assess the status of CEMS in various industries. Through our survey, we found out some labs that provided CEMS-related services in Uttar Pradesh as shown in Table 1.

6 Discussion and Conclusion

6.1 CEMS Regulation, Certification and Maintenance

CEMS regulation, certification and maintenance heavily rely on the quality assurance and quality control (QA/QC) of CEMS devices and data. QA/QC includes confirming the accuracy, precision, reliability and validity of the CEMS measurements and ensuring they meet performance specifications and standards. As per the CPCB, 2017, the integrity and quality of the data are maintained through this process. QA/QC encompasses rectifying any errors or deviations that may arise due to various factors, including instrument malfunction, calibration drift, sampling errors, data transmission errors, etc. (CPCB, 2018).

Depending on the pollutant type, measurement technique, regulatory requirement and industry sector, QA/QC for CEMS can involve different methods and procedures. Calibration of a CEMS device entails the adjustment or verification of its response to a known concentration or value of a pollutant or parameter. Certified reference materials or methods that can be traced to national or international standards are used for calibration. Regular intervals, like daily, weekly or monthly, are commonly chosen for calibration, but it can also be done when there are noticeable changes in the CEMS device's performance or operating conditions. It is crucial to highlight that calibration must be conducted by professionals with proper training to guarantee precise and dependable measurements. Testing and verifying the performance of a CEMS device against a reference method or a standard is the main focus of performance evaluation. The purpose of performance evaluation is to verify if the CEMS device meets the acceptance criteria and specifications for accuracy, precision, linearity, stability, etc. This evaluation is typically carried out during installation or commissioning of the device, after any significant repair or modification, or at regular intervals as mandated by the regulation (Singh, 2017; Ins Tool, 2023). The process of auditing involves inspecting and reviewing the CEMS device and data to ensure compliance with regulatory requirements and standards. The quality and integrity of the CEMS device and data are verified by an independent or authorized agency or person through an audit. The audit may also entail performing on-site tests or measurements using audit devices or methods to compare them with the CEMS device and data (Kuiken & Gaston, 2009; CPCB, 2018).

In developed countries like the European Union (EU), the United States of America (USA) and Japan, CEMS is extensively utilized for controlling industrial air pollution and ensuring adherence to environmental regulations. CEMS has a vital function in overseeing and managing emissions from diverse industries in these nations. The introduction of CEMS in India for 17 categories of industries and common pollution treatment facilities happened in 2014 by the CPCB. CEMS data cannot be utilized for legal and compliance purposes in India for multiple reasons despite duration of over seven years of implementation. Nevertheless, it remains suitable for various other applications like monitoring and analysis (CPCB, 2018; CSE, 2022).

To address this challenge, India urgently needs a certification system for CEMS devices. This system should ensure their quality, accuracy and performance. Europe, USA and other countries have established well-framed certification systems for CEMS devices, which India can learn from. However, it should also consider its unique challenges and requirements while developing its own system. The extensive testing and verification of CEMS devices by independent agencies are the basis for these systems, conducted following defined standards and protocols. They also involve clear roles and responsibilities of stakeholders, definitive guidelines and periodic quality assurance checks. According to the CSE report 2022, diverse certification systems are employed by different countries for CEMS. The majority of these countries have adopted European standards as the foundation for their certification processes. The information is summarised in Table 8.

By using these standards, compliance with European regulations is ensured and measurements are accurate and reliable. The respective agencies list the certified CEMS devices on their websites. Similarly, USA has adopted CEMS performance checks during installation at the site. To maintain accurate data, CEMS devices are tested periodically for quality assurance after being installed. The USA has a web-based system named Emission Collection and Monitoring Plan System (ECMPS) that gathers, validates, audits and reports CEMS data from industries to the regulatory authority. Ensuring accurate and transparent reporting of emissions in the country is a crucial role played by this system. Standards like 40 CFR Part 60 Appendix B dictate the performance specifications of CEMS devices in USA (CSE, 2022).

According to CSE report CEMS Certification System in India a certification system for CEMS devices that can be implemented by CPCB in collaboration with other stakeholders such as SPCBs, industries, common pollution treatment facilities, manufacturers, suppliers, testing laboratories, accreditation bodies, research institutes, civil society groups etc. The proposed model consists of four main components:

***Product certification*:** This component involves testing and verification of CEMS devices performed by an approved testing facility following established procedures and benchmarks. The testing laboratory issues a certificate of conformity to the manufacturer or supplier if all relevant criteria for performance specified by CPCB are satisfied accordingly with regards to this particular device, then obtaining a certificate of conformity becomes feasible. The certificate remains effective for a designated duration or until any substantial modification or change occurs with the device. The CPCB website contains a list of certified CEMS devices including their technical specifications and test results.

***Installation and calibration*:** This component involves installation and calibration of CEMS devices at the site by qualified and trained personnel. The installation and calibration are done according to the manufacturer's instructions and the CPCB guidelines. The installation and calibration reports are sent to the SPCB to await approval. The report is verified by the SPCB the user receives a certificate of approval. In case both device installation and calibration are done correctly. For a certain duration, the certificate remains valid until any major modification or change in the device or the site.

The SPCB will review the CEMS calibration report submitted by the user or operator and verify that it meets the guidelines and standards specified by the CPCB and the SPCB. The SPCB will also check the validity and accuracy of the calibration data and the performance evaluation of the CEMS device. The SPCB will approve the CEMS calibration report if it is satisfied with the quality and reliability of the CEMS device and the data generated by it. The SPCB will issue a CEMS calibration approval letter to the user or operator, specifying the conditions and requirements for the CEMS operation, maintenance, quality assurance, data reporting and compliance determination. The SPCB will also conduct periodic audits and inspections of the CEMS device and the data reported by it to ensure the continuous compliance of the source with the emission standards and regulations (CPCB, 2018; CPCB, 2017; CPCB, 2014; SPCB, 2022).

***Operation and maintenance*:** Proper functioning of CEMS devices relies on users performing operational tasks while also adhering to both manufacturer's instructions along with CPCB guidelines as shown in Table 3

***Audit and surveillance*:** This component involves audit and surveillance of CEMS devices by the SPCB or an authorized agency. The audit and surveillance process includes inspections of CEMS devices to verify compliance with correct installation measures. They also verify calibration accuracy and evaluate overall data quality. Random or scheduled intervals for conducting the audit and surveillance activities are utilized. Additionally, the CPCB takes into account complaints or notifications for review. For further steps, the audit and surveillance report has been handed over for advancing into the next phase. Corrective actions like warnings, penalties, suspensions or cancellations of certification or approval are possible for the CPCB. This is done in case of identifying any non-compliance issue or discrepancy.

The suggestion is to establish a certification and quality assurance system following the patterns used in India as per EU norms is shown in Table 10 (CSE, 2022).

Improving the quality and credibility of CEMS data can be transformative with the implementation of the proposed certification system for CEMS devices in India. The model can also boost the indigenous manufacturing of CEMS devices. The effective implementation and enforcement by CPCB and other stakeholders determine the success of the model.

Consequently, a resilient and thorough QA/QC system for CEMS in India needs to be created. By establishing sector-specific guidelines and protocols for QA/QC that consider technical feasibility and regulatory requirements, this system aims to address its challenges and limitations. Moreover, it must support the competency and infrastructure of laboratories and authorities for calibration and performance appraisal. To improve their skills and knowledge, personnel involved in QA/QC should undergo training and awareness programs. Essential to note is the improvement needed in the coordination and cooperation among diverse stakeholders participating in QA/QC, including regulators, industries and service providers. It is also important to implement efficient monitoring and enforcement mechanisms for QA/QC, including penalties, incentives and rewards.

6.2 Financial Challenges

The impact of CEMS implementation in India on industrial emissions and compliance is evaluated in a report by the International Initiative for Impact Evaluation. The report states that the introduction of CEMS did not lead to noteworthy decreases in emissions or enhancements in compliance. The report also identifies some financial gaps in CEMS implementation. The barriers encompass the expensive nature of CEMS devices and their installation, the absence of monetary rewards and penalties for industries and the regulators' constrained budget and resources (3ie, 2020).

According to a report by the Centre for Science and Environment (CSE), one possible details of regulators' budget constraints faced by the regulators in implementing CEMS in India is the lack of adequate financial resources and infrastructure to support the CEMS certification and quality assurance system. The report states that the regulators need to invest in setting up testing and verification facilities, hiring and training qualified personnel, developing and maintaining data management systems, and conducting regular audits and inspections of CEMS devices and equipment. The report also suggests that the regulators need to explore various funding mechanisms, such as fees, fines, subsidies, incentives, etc., to sustain the CEMS certification and quality assurance system (CSE, 2016).

Another report by CSE titled "CEMS Certification System in India - CSE Proposal" provides a proposal for a certification and quality assurance system for CEMS in India, based on the best practices of developed countries such as USA and Europe. The report identifies the key components of such a system, such as testing and verification of devices by independent agencies, defined roles and responsibilities of stakeholders, and guidelines and protocols for installation, operation, maintenance and data reporting. The report also suggests a roadmap for implementing the proposed system in India, along with the expected benefits and challenges. The report does not provide a specific estimate of the CEMS cost in India, but it mentions that the cost of CEMS devices and equipment in India ranges from Rs 10 lakh to Rs 1 crore per unit, depending on the type and quality of the device (CSE, 2022).

The Centre for Science and Environment (CSE) suggests implementing a CEMS certification system in India, following global standards. In addition, the certification systems in other countries are addressed, while the key components and benefits of the proposed certification system are outlined. The report also estimates the cost of CEMS certification for different sectors and suggests some possible sources of funding, such as user fees, emission trading schemes, green bonds, etc. (CSE, 2022).

A website by ABB, a global leader in CEMS technology, that provides an overview of emission monitoring and its applications. In India, ABB's website showcases various CEMS projects implemented for sectors such as power, cement, steel, etc. Moreover, the website highlights the advantages of CEMS for industries, including increased profitability, enhanced compliance, reduced emissions and improved efficiency (ABB, 2021). According to Down To Earth (2022). , certain of these gaps are-

- The expense associated with CEMS devices and their installation might discourage certain industries and embracing them to consider cheaper and inferior CEMS device options. Whereas, accurate and reliable emissions monitoring requires the crucial investment in high-quality CEMS devices.
- Industries are not motivated financially to meet emission standards or submit accurate CEMS data due to the absence of incentives and penalties. The progress towards achieving environmental sustainability is impeded by this.
- Limited budget and resources hinder regulators from effectively monitoring and enforcing CEMS data and taking corrective or punitive actions against non-compliant industries.
- The lack of indigenous manufacturing and supply of CEMS devices that meet the performance standards and requirements of CEMS in the Indian context.

For adoption of international standard certification system in India various kinds of issues have found such as Lack of technical capacity, data quality and reliability, enforcement and verification mechanisms, and stakeholder participation (3ie, 2020). High cost and maintenance of CEMS, lack of skilled manpower and infrastructure, data security and privacy issues, and low compliance and enforcement levels (CPCB, 2017). Absence of a structured methodology for regulators to use and act upon CEMS data and Lack of awareness, financial constraints, technical difficulties and bureaucratic hurdles (CSE, 2022).

That is why India needs to develop indigenous certification system of CEMS to ensure the quality and reliability of the devices and equipment used for monitoring emissions from various industries and sources. No existing certification system for CEMS equipment takes into consideration India’s climatic conditions, which may affect the performance and accuracy of the devices (Down to Earth, 2023). India lacks independent agencies and laboratories that can test and verify the CEMS devices and equipment according to the national and international standards and specifications (CPCB, 2018). India needs to promote the ‘Made in India’ program by encouraging local manufacturers to develop CEMS devices and equipment that can meet the regulatory and compliance requirements. India needs to support the implementation of the National Clean Air Programme (NCAP) by providing quality assurance and verification of the data generated by the CEMS devices and equipment across the country (CSE, 2015).

In India, the implementation of CEMS can impose a significant financial burden, particularly on small and medium-sized enterprises (SMEs). To address this issue, the government has a range of potential measures to enhance the affordability of CEMS within the country. These measures include government subsidies, tax incentives, domestic production of CEMS equipment, the development of cost-effective CEMS technologies, fostering public-private partnerships, and collaborating with private enterprises to facilitate the adoption of CEMS.

According to CPCB, the installation and operational costs associated with CEMS in India can vary significantly, ranging from ₹10 lakh to ₹1 crore. The study also found that the cost of CEMS varies depending on the size and complexity of the industry, as well as the type of CEMS being installed.

Recently, the government has floated several policies that make CEMS more affordable and accessible. This includes the green credit limits policy in 2023 and the formulation of the Industrial Investment and Employment Promotion Policy for Uttar Pradesh in 2022, both of which are designed to incentivize and help to facilitate the adoption of CEMS by industries in India.

According to the Industrial Investment & Employment Promotion Policy of Uttar Pradesh for 2022, there is a provision to provide financial aid to qualified industrial establishments for the installation of pollution control equipment, specifically Continuous Emission Monitoring System (CEMS) devices. The policy states that eligible industrial units have the opportunity to receive a capital subsidy equal to 50% of the expenses associated with machinery and equipment (excluding land and buildings), with a maximum limit of ₹1 crore per unit. This subsidy aims to facilitate the implementation of measures to control pollution, including the utilization of CEMS devices. Furthermore, the policy encompasses a range of other incentives for eligible industrial units operating within the state, which includes subsidies for land, interest, exemption from electricity duty, and waiver of stamp duty, among others (UP IIEP, 2022).

Recently GOI launch The Green Credit Mechanism, as part of India's Green Credit Policy which aims to incentivize industries to adopt environmentally friendly practices. The program allows for the trading of green credits, providing a market for companies to buy and sell credits based on their environmental performance. Participants in the GCP can earn tradable credits for their compliance with pollutant emission standards. These credits can be traded in the market, providing a financial incentive for environmentally friendly practices. To leverage the benefits of the GCP, entities can utilize CEMS. The recorded data from CEMS is subject to validation as per the guidelines set by the CPCB. The data must meet certain quality and accuracy criteria to be considered valid. If data from CEMS is duly validated and demonstrates compliance with pollutant emission standards, it can be used to generate credits under the Green Credit Programme. This means that entities can earn credits based on their verified emissions reductions. The GCP encourages businesses to adopt eco-friendly practices and offers a market-driven mechanism to reward their efforts. The integration of CEMS-based monitoring ensures transparency and accuracy in emissions reporting, further enhancing the effectiveness of the program (BT, 2023; GCP, 2023).

In India, the environmental governance and outcomes can also be strengthened. User fees or emission trading schemes can also generate revenue for the regulators through the system. The certification process and regulatory capacity can be improved by utilizing this revenue. CEMS devices indigenous manufacturing and supply can be boosted by the system so that vision of 'Make in India' is fulfilled.

6.3 Capacity Building and Training

In India, there is only one agency, the Centre for Science and Environment (CSE), in New Delhi, which provides most of the training programs related to CEMS in India. It will provide proper programs that showcase some of the initiatives and capacity-building training programs undertaken by CSE to promote CEMS implementation and awareness in various industries and regions. The Environmental Training Unit (ETU) of the Central Pollution Control Board, Delhi organized an online training programme of three days through ESCI Hyderabad. The detail of training programme is shown below in Table 11.

CSE organized a one-week training programme on CEMS in collaboration with JSW Steel in 2016. The training programme was designed to develop the knowledge base and skills of environmental regulators on various aspects of CEMS, such as device selection, installation, operation, maintenance, data transmission, inspection and compliance check (CSE, 2016). Another training programme on CEMS and CEQMS (Continuous Effluent Quality Monitoring System) organized by CSE in 2018. The training programme was aimed at developing the knowledge base and skills of environmental professionals from industries, consultants and academia on various aspects of CEMS and CEQMS (CSE, 2018).

Integrated Online and Onsite training programme on Continuous Emission and Effluent Monitoring System was again conducted by CSE on CEMS and CEQMS in 2020. The training programme consists of two parts: basic learning and advanced learning (CSE, 2020).

CSE-SEPA Online Training Programme on CEMS & CEQMS is an internet-based course offered by the CSE that covers topics related to CEMS and CEQMS in collaboration with the Swedish Environmental Protection Agency (SEPA) for officials of State Pollution Control Boards. Regulators are targeted by the programme for enhancing their understanding and expertise in different areas of CEMS and CEQMS including device selection, installation procedures, operation techniques, maintenance practices, data transmission methods, inspection protocols and compliance verification (CSE, 2021a).

Capacity building initiative for Regulators of CEMS & CEQMS an online training programme was designed with collaboration of CSE-SEPA on CEMS and CEQMS. The workshop addresses the implementation or planned implementation of the training programmes learnings by the respective

PCBs. Moreover, the workshop incorporates Swedish experts who discuss their perspectives on their strategies for achieving effective execution of their action plans and policies (CSE, 2021b).

The online course on CEMS and CEQMS for technology selection, its installation, Data Handling and its Audit Methodology, focuses on the training programme provided by CSE for environment professionals from industries, consultants and academicians. In the course, participants will learn about measurement techniques, instrumentation, calibration, audit, data management, reporting, etc., covering both theoretical and practical aspects of CEMS and CEQMS. (CSE, 2021).

Government should offer training to the personnel handling and managing CEMS. The SPCBs can conduct these trainings. CEMS equipment training should encompass installation, calibration and maintenance procedures. A certification program for personnel who operate and maintain CEMS could be established by the government. Capacity building programs can also be offered by the government to industries, aiming to make them realize the significance of CEMS. In addition, they have the ability to educate them on utilizing the gathered information. The capacity building programs can cover topics such as emissions reduction strategies, energy efficiency and environmental management systems. A platform can be established by the government for industries to exchange best practices for reducing emissions.

Recently, DoEFCC, GoUP has proposed UP Clean Air Management Project under the World Bank Program for Air shed management in IGP states. The Apex Institute will act as a central hub for the UP Clean Air Management Project. It will provide crucial support to the 15 Knowledge Centers located in various educational institutions across the state. The Apex Institute will offer comprehensive capacity building support to the Knowledge centers. Since, there is a lack of institutions that provide CEMS related training in UP, it will also facilitate the development of training programs, workshops and refresher courses related to air quality monitoring devices including CEMS to enhance the knowledge and skills of professionals engaged in air quality management. These programs will be delivered through online and offline platforms.

6.4 Data Management System

Displaying information from different sources in a single interface is made possible by a IoT-based dashboard tool through metrics, logs, alerts and text can be displayed. Users can utilize it to monitor, analyze and visualize data from CEMS devices on various platforms and locations.

A potential strategy for developing IOT-based dashboard in CEMS in India is to establish by collaborations with local technology companies and government agencies. Ensuring the successful implementation and adoption of the dashboard, this collaboration can leverage their expertise and resources. Pilot projects and feedback from end-users can yield valuable insights for improving and customizing the dashboard to cater to the specific requirements. The possible way forward is-

- To select a suitable cloud platform and dashboard tool that can integrate with the CEMS devices and data sources and provide the required functionality, security, scalability and reliability, careful evaluation and analysis of available options is necessary.
- Creating a dashboard that can showcase pertinent information for diverse user roles and scenarios, like regulators, plant managers, operators, and auditors. User-friendliness, interactivity and information availability are important qualities of the dashboard.
- To analyze and assess the dashboard with the end-users and stakeholders. To gather feedback for betterment and optimization.
- To deploy and maintain the dashboard and ensure its availability, performance and accuracy.

6.5 Collaboration and Partnerships

The successful adoption and operation of CEMS relies heavily on collaboration and partnership among different stakeholders. A report of a collaboration and partnership of CEMS can be seen in a project led by 3ie, an organization that evaluates the outcomes of development interventions. By introducing CEMS in India, the project analyzed the consequences on pollution emissions and adherence to regulatory standards. To implement CEMS and monitor their performance, the project required collaboration with CPCB, SPCBs and industrial plants. The project also involved conducting surveys, interviews, focus group discussions and field experiments to collect data and analyze the outcomes. The project found that CEMS can reduce emissions by improving the information and enforcement of environmental regulations. Different stakeholders can gain multiple benefits through collaboration and partnership of CEMS. The stakeholders encompass academia, industry, government, civil society and the environmental agencies. The challenges of CEMS can be effectively addressed and opportunities can be maximized through collaborative efforts among these stakeholders. Moreover, they can contribute their knowledge, skills, resources and connections to generate value and make a difference for both themselves and others (Greenstone et al., 2020; CEMS, 2023).

In recent years, India has witnessed successful collaborations and partnerships for the implementation of CEMS. CPCB and the German development agency, GIZ, form a prominent partnership. This partnership focused on building capacity for CEMS implementation. CPCB educated industry personnel, regulators and stakeholders on CEMS technology and its implementation through training programs. The formulation of a national CEMS policy and guidelines was supported by GIZ through technical assistance (GIZ, 2019).

MoEFCC and UNDP had another successful collaboration aimed to enhance air quality monitoring and management in Indian cities. Pilot projects were implemented to showcase CEMS feasibility and effectiveness. UNDP provided technical assistance for the development of a national air quality management plan, encompassing CEMS integration (MoEFCC, 2019).

A multi-stakeholder approach is vital for further advancing CEMS implementation and involving the private sector can augment efforts by providing expertise and resources. Supported by government incentives like tax breaks or subsidies, it can further enhance the impact. Civil society organizations can play a pivotal role in creating awareness about CEMS importance. They can also monitor implementation and offer feedback. Sharing best practices and experiences through international collaborations with organizations providing technical assistance and funding is essential for optimal CEMS implementation. Ensuring that countries have access to the required resources and knowledge these collaborations aid in effectively implementing and maintaining their CEMS. For instance, the Partnership for Clean Indoor Air (PCIA) and the Sustainable Development Goals (SDGs) has shown the effectiveness of multi-stakeholder approaches in addressing global challenges. CEMS implementation is vital to tackle air pollution in India. The successful execution relies on collaborations and partnerships with various stakeholders. Incorporating government, development agencies, private sector, civil society and international organizations through a multi-stakeholder approach, India can secure the effectiveness, sustainability and inclusivity of CEMS implementation. The collaborative effort will result in better outcomes and all stakeholder's diverse needs will be effectively addressed.

Figure 27 shows how CEMS can be effectively implemented in India to reduce emissions from industries and mitigate issues consisting of information reliability, device certification and competency gaps. This accomplishment is a result of timely performance check and maintenance, regulatory system development, capacity building and guidance. The implementation of CEMS results in positive outcomes, together with proper environmental compliance and enforcement, better credibility and accuracy of CEMS information, and improved overall performance and reliability.

There are several issues related to CEMS services in India, such as the lack of clear guidelines and standards for CEMS selection, installation, calibration and quality assurance. The high initial and recurring costs of CEMS equipment (especially for small and medium enterprises), low reliability and accuracy of CEMS data due to technical glitches, tampering or manipulation by industrial units or service providers, poor data management and transmission systems that result in data loss, delay or inconsistency and inadequate regulatory capacity and enforcement mechanisms to monitor and verify CEMS data and ensure compliance (3ie, 2020: CSE, 2016; CSE, 2022).

These issues pose challenges for the effective implementation and regulation of CEMS in India. Possible solutions to address these issues include developing and disseminating clear and uniform guidelines and standards for CEMS selection, installation, calibration and quality assurance across different sectors and regions as per CPCB guidelines. Providing financial incentives and subsidies to industrial units for adopting CEMS technology and ensuring regular maintenance and calibration using government schemes like GCP and UPIIEP policies, providing capacity building support through the UPCAMP project, since there is a lack of institutions that provide CEMS-related training in UP and enforcement mechanisms by increasing the frequency and quality of inspections, audits and penalties as per CPCB guidelines.

Credit authorship contribution statement

Ravi Prakash Srivastava: Conceptualization, Data curation, Formal analysis, Methodology, Visualization, Writing – original draft. **Sahil Kumar:** Methodology, Writing – review & editing. **Ashish Tiwari:** Conceptualization, Funding acquisition, Supervision.

Declaration of competing interest

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

Data availability

The authors do not have permission to share data.

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Abbreviations

AST: Annual Surveillance Test

CAGR: Compound Annual Growth Rate

CAGR: Compound Annual Growth Rate

CEMS: Continuous Emissions Monitoring Systems

CEQM: Continuous Effluent Quality Monitoring System

CEQMS: Continuous Effluent Quality Monitoring Systems

CETPs: Common Effluent Treatment Plants

CFPs: Coal Fire Power Plants

CFR: Code of Federal Regulations

CGA: Cylinder Gas Audits

CIED: Chinese Industrial Emissions Database

CPCB: Central Pollution Control Board

CSE: Centre for Science and Environment

CSIR-NPL: Council of Scientific and Industrial Research-National Physical Laboratory

CTO: Consent to Operate

DAMC: Data Acquisition and Management Centre

DAS: Data Acquisition System

DoEF&CC: Department of Environment, Forest & Climate Change

ERT: Electronic reporting tool

ESCI: Engineering Staff College of India

ETS: Emission Trading Scheme

ETU: The Environmental Training Unit

EU: European Union

GCP: Green Credit Policy

GPCB: Gujarat Pollution Control Board

HCGA: Harvard Centre for Geographic Analysis

ICSC: International Centre for Sustainable Carbon

IED: Industrial Emissions Directive

LEP: Vietnam's Law on Environmental Protection

MCERTS: Monitoring Certification Scheme

MoEF&CC: Ministry of Environment, Forest and Climate Change

MSMEs: Micro, Small and Medium Enterprises

NABCB: National Accreditation Board for Certification Bodies

NABL: National Accreditation Board for Testing and Calibration Laboratories

NCAP: National Clean Air Program

NOx: Nitrous Oxides

OCEMS: Online Continuous Emissions Monitoring Systems

OECD: Organization for Economic Cooperation and Development

PM: Particulate Matter

PTZ: Pan-Tilt-Zoom

QA/QC: Quality Assurance/ Quality Check

QAL: Quality Assurance Level

QAP: quality assurance procedures

QSTI: Qualified Source Testing Individual

QSTO: Qualified Source Testing Observer

RAA: relative accuracy audit

RATA: Relative accuracy test audit

RTDMS: Real Time Data Monitoring System

SEPA: Swedish Environmental Protection Agency

SEPA: Swedish Environmental Protection Agency

SES: US Source Evaluation Society

SO_2: Sulphur Dioxide

SOPs: Standard Operating Procedures

SPCB: State Pollution Control Board

SRM: Standard Reference Method

STA: UK Source Testing Association

TUV: Technischer Uberwachungs-Verein

UBA: Umweltbundesamt

UKEA: UK Environment Agency

UNEP: United Nations Environment Program

UPCAMP: Uttar Pradesh Clean Air Management Project

UPIIEPP: UP Industrial Investment and Employment Promotion Policy

UPPCB: Uttar Pradesh State Pollution Control Board

US EPA: United States Environment Protection Act

VOCs: Volatile Organic Compounds

WHO: World Health Organisation

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