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A review on Exploring Low-Cost Sensors Efficacy with Digital display System in measuring of Indoor and ambient Air Quality parameters within India (PRISMA model)

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Abstract
Low-cost sensors-based air quality monitoring in India is the need of the hour since existing reference-grade monitoring stations are expensive, limited in number and coverage. However, low-cost sensor application potential, status of existing constraints in implementation were unknown due to non-existence of review on current status of sensor-based monitoring in India. Hence, this review investigates the potential of low-cost sensors for monitoring air quality in India, with a particular focus on indoor environments, policy status, problems in sensor applications by conducting a comprehensive search, collation, and analysis of the literature in the relevant fields over the past two decades using PRISMA guidelines. A diverse range of low-cost sensors are available for measuring PM, gaseous pollutants, and meteorological parameters. Low-cost sensors-based projects are utilizing low-cost sensors for air quality monitoring, including the CHAI, the TAPHE-2, SATVAM and the ATMAN initiative. Pilot scale calibrated sensors were used to monitor air quality in six major locations under the ATMAN initiative. Low-cost monitors used by individuals /organizations were majorly not validated and were only qualitative. It is found that the low-cost sensors deployed have lower accuracy compared to reference-grade monitors in Indian regions. There were no agency or government authorized calibration procedure or data validation techniques available causing paucity in expansion of air quality monitoring. The following recommendations need to be addressed urgently to solve the above issue (i) To develop robust calibration procedures and invest in research to improve sensor accuracy and reliability. (ii) Explore the use of machine learning and data analytics for improved air quality prediction and forecasting. (iii) Expand government initiatives and public awareness campaigns to promote the use of low-cost sensors for air quality monitoring.

INTRODUCTION

Air pollution is a major global health threat, silently stealing years from lives and costing economies billions. Exposure to both outdoor and interior air pollution has the potential to reduce the average lifespan of a child born today by 20 months. However, in South Asia (namely Bangladesh, India, Nepal, and Pakistan), where air pollution is particularly severe, the loss of life can extend to almost 2 years and 6 months (State of Global Air Report, 2019). Annually, the combined impact of ambient air pollution and residential air pollution leads to 6.7 million premature deaths across globe and 1·67 million deaths in India. Out of which about 0.98 and 0.61 million life losses were attributed to the outdoor and indoor particulate matter pollution, respectively (Desouza et al., 2023).

It is important to note that India is experiencing extensive urbanization, 36% of the people currently reside in cities as of 2022 (Urban population (% of total population) - India | Data (worldbank.org) and is expected to reach 40-45% by 2050. The rapid growth of cities, industries, and population in India is a major contributor to the high levels of aerosol pollution in the subcontinent (Kaur and Pandey, 2021). With the above perspective, the interactions between outdoors and indoors are inevitable and this has serious implications for the health of people dwelling in cities. Indoor environments are five times more vulnerable than outdoor environments owing to the pollution exposure duration and quantity of pollution (Sharma et al., 2022). Approximately 2.3 billion individuals globally, accounting for roughly one-third of the total population, utilize open fires or inefficient stoves that rely on kerosene, biomass (such as wood, animal dung, and crop waste), and coal as indoor fuel sources. This practice leads to the production of detrimental household air pollution. In 2020, household air pollution caused over 3.2 million deaths, with over 2,37,000 of those deaths occurring in children under the age of five.

In India air pollution is mainly monitored through the National Air Quality Monitoring Programme (NAMP) in 344 cities/towns using reference grade instruments. Central Pollution Control Board (CPCB) monitors Sulphur Dioxide (SO2), Oxides of Nitrogen as NO_2 and Suspended Particulate Matter (SPM) and Respirable Suspended Particulate Matter (RSPM/PM10) in all locations. Hydrogen Sulphide (H_2S), Ammonia (NH_3), and Polycyclic Aromatic Hydrocarbons (PAHs) were also monitored only in 10 metro cities of the country. It is important to note that the monitoring represents only 6-8% of monitoring recommendations by IS:5182 (part14) and there is an additional need for 959 PM monitors, 643 SO_2 monitors, 630 NO_2 monitors, and 320 monitors for CO and surface ozone (Somvanshi et al., 2023). Continuous Ambient Air Quality Monitoring Station (CAAQMS) is a network of monitoring stations set up over 274 stations in 144 cities covering 24 states and union territories to track air quality (https://cpcb.nic.in/real-time-air-qulity-data/).However, all stations do not have enough data or monitors to represent the air quality index. For instance, 47% of the urban and rural population were outside the monitoring grid. While there is no publicly available information about household air pollution. In summary, there is an urgent need to address both ambient and household air pollution to improve public health in India.The fast development of low-cost sensors has made improved spatial and time resolution individual air pollution monitoring possible in recent years. The future of air (and health) monitoring is predicted to be democratized, high-resolution, and interconnected, providing 'big data' enabling difficult, but more inclusive study (Snyder et al.,2013). In the case of developed countries like the USA and Europe the deployment of low-cost sensors was gaining significance since reference grade monitors are costly and have limited coverage. The advantage of low-cost sensors has led to an increase in purchase by individuals and organizations to monitor air quality (so far 5602 low-cost sensors to 1192 reference grade instruments are available in the US as of 2020). China is estimated to have over 30,000 air pollutant sensors in operation, with a focus on areas with the most severe air quality problems. More than 10,000 sensors are in northern China. Beijing alone has had over 2,000 PM sensors monitoring air quality since 2016. It is important to note that low-cost sensors tend to be less representative of both concentrations and demographic characteristics when compared to reference grade EPA monitors (deSouza and Kinney,2021). Indoor sensors typically focus on pollutants relevant to indoor environments like VOCs, CO2, and particulate matter, while outdoor sensors measure outdoor-specific pollutants such as ozone and nitrogen dioxide. Measurements done using outdoor low-cost particulate matter (PM) and gas sensors are influenced greatly by environmental conditions such as relative humidity (RH) and temperature, whereas indoor undergo fewer changes in the RH, so the sensors are not much influenced. Low-cost sensors used outdoors face the weather and high pollutant concentrations, but not the indoor sensors. Additionally, outdoor sensors may not be sensitive enough to detect low concentrations of indoor pollutants accurately. Therefore, specialized indoor air quality sensors are necessary to monitor and improve indoor air quality effectively. Expanding ambient monitoring networks and providing individuals with access to concentration data and practical information, such as air quality, could potentially eliminate the need for sensors or monitors to evaluate their exposure to ambient air pollution. It is essential to monitor personal exposure to determine the amount of indoor source exposure and combustion products, such as ultrafine particles (< 0.1 μm), in the home (Morawska et al., 2018). However, there are certain research problems that have to be addressed before implementing the low-cost sensor technology in developing countries like India where the complexity is high due to population, geography and multitude of sources.From the literature survey most of the air quality and sensor review focused on global context, which reviewed relatively few studies (2-10) in context of India, while reviews pertaining to indoor air quality in India dealt with public health and exposure-based problems associated with indoor air quality in India. Since India is emerging in the technological frontier there is a need to investigate low-cost sensor technology-based air quality monitoring, it's status and challenges to make informed policy decisions and research in the future.

This is the first review of low-cost sensor studies and their applications in air quality monitoring in India from peer-reviewed and grey literature. Our scope and discussion focus to address the following research questions: (i) What are the major categories of low-cost sensors and their utilization in analyzing indoor air quality in India? (ii) What are the challenges encountered while evaluating indoor air quality with low-cost sensors? (iii) What are the efforts in India that aim to enhance sensors for better comprehension of indoor air quality? (iv) What are the primary policy measures implemented by the government to address the demand for studying air quality, particularly in terms of monitoring instruments? Additionally, what is the present state of these measures? These benefits and developments show how low-cost sensors might reestablish air pollution and public health efforts.

2.Methodology

Preferred Reporting Items for Systematic Reviews and Meta-Analysis (PRISMA) method an evidence synthesis tool, was chosen for reviewing indoor air quality (IAQ) monitoring studies employing low-cost sensor technologies due to several key reasons i.e., structured approach, comprehensive search strategy, transparent reporting, risk of bias assessment, data synthesis, and presentation.

For the literature survey ScienceDirect, Web of Science, IEEE Xplore, PubMed, and Google Scholar were chosen. In the scientific database, the following search terms were used, "Indoor air quality monitoring using low-cost sensors", "Household air quality monitoring in India", "ambient air quality monitoring using low-cost sensors in India", "Government policy for indoor air quality monitoring in India", "policy amendments and development4 for air pollution in India", "interaction studies of outdoor and indoor air pollution using sensors in India". Research articles, reviews, short communications, and reports were retrieved from the above scientific databases spanning between 2000 to 2024. We have collected 97 papers using the PRISMA method. We used VOS viewer (version 1.6.2) for identifying the connections between the studies using co-occurrence of words from the title and abstract section of the paper rather than just keywords found in the paper. For VOS viewer mapping of most frequent author keywords, a minimum occurrence of 5 was used as a cut-off point for inclusion of the keyword in mapping analysis.

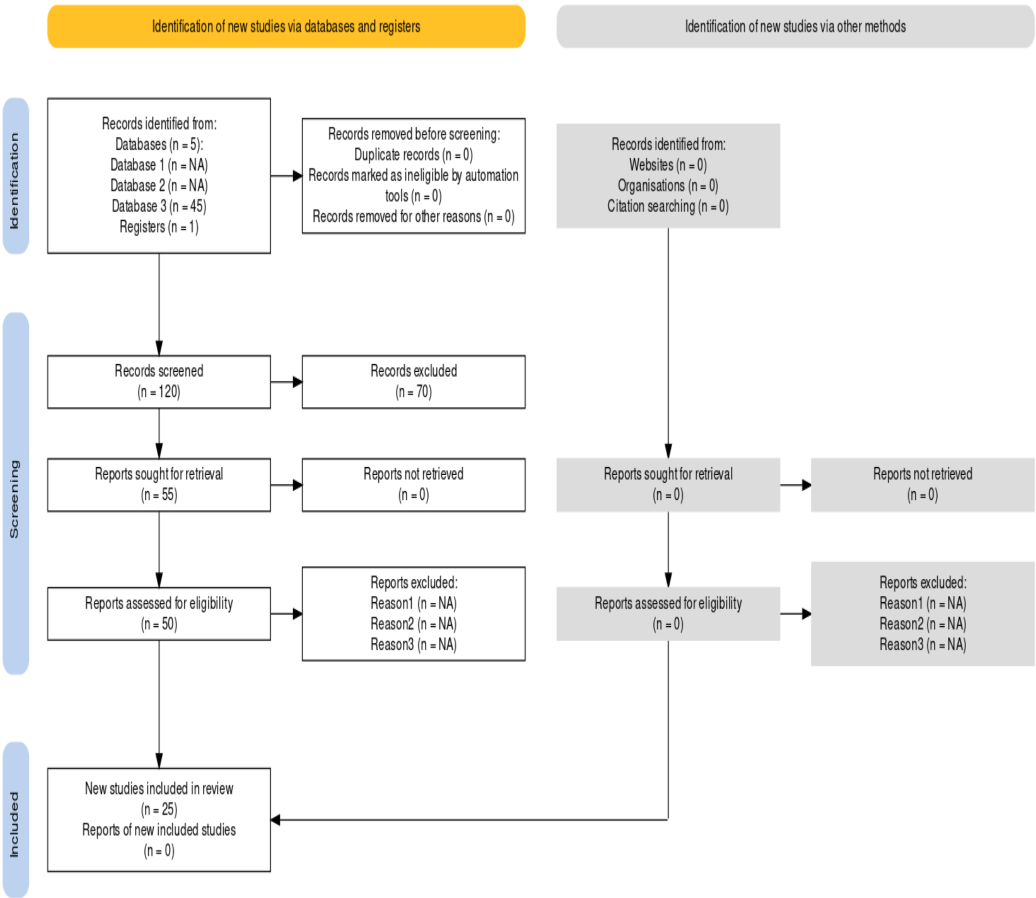

Figure 1 : Flow diagram of selection of studies using PRISMA guidelines.

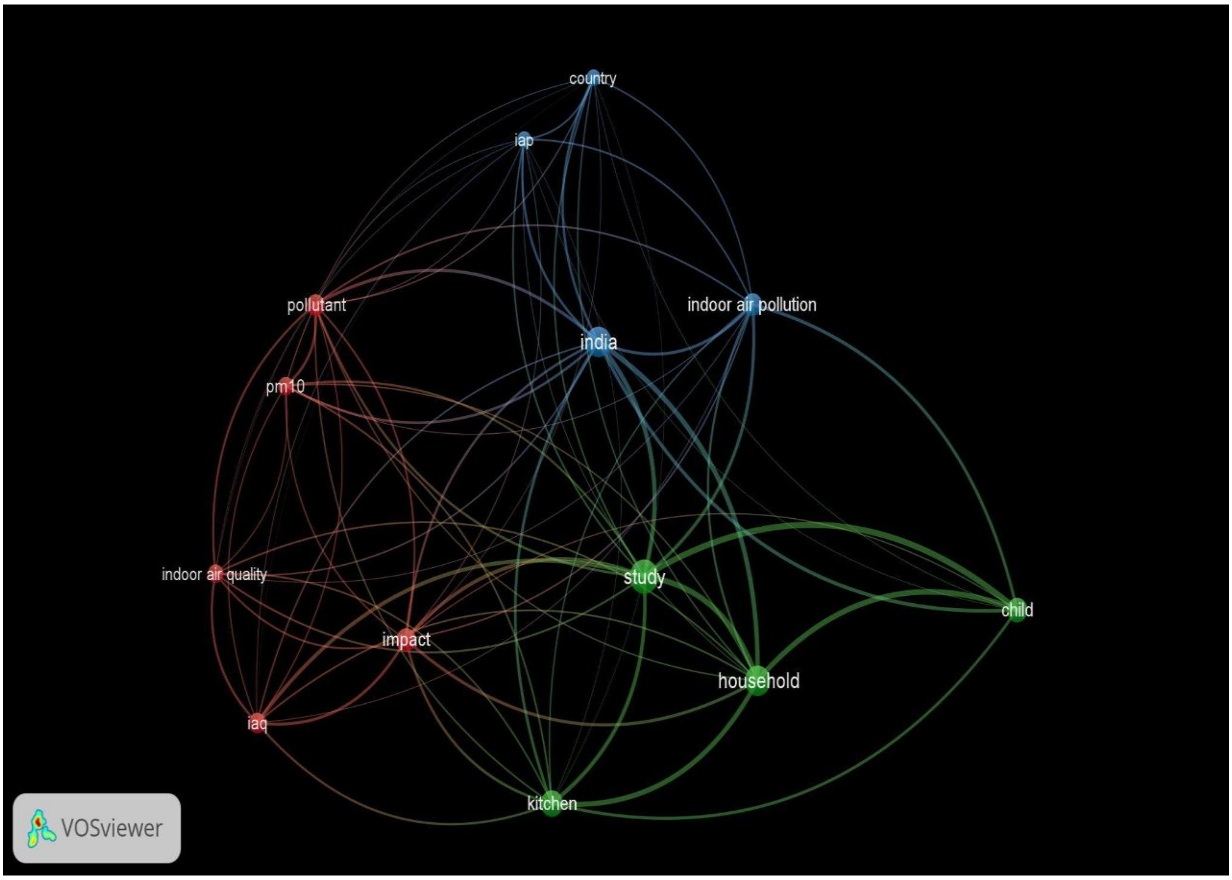

Figure 2a: Map of co-occurrence of the keywords during the study period.

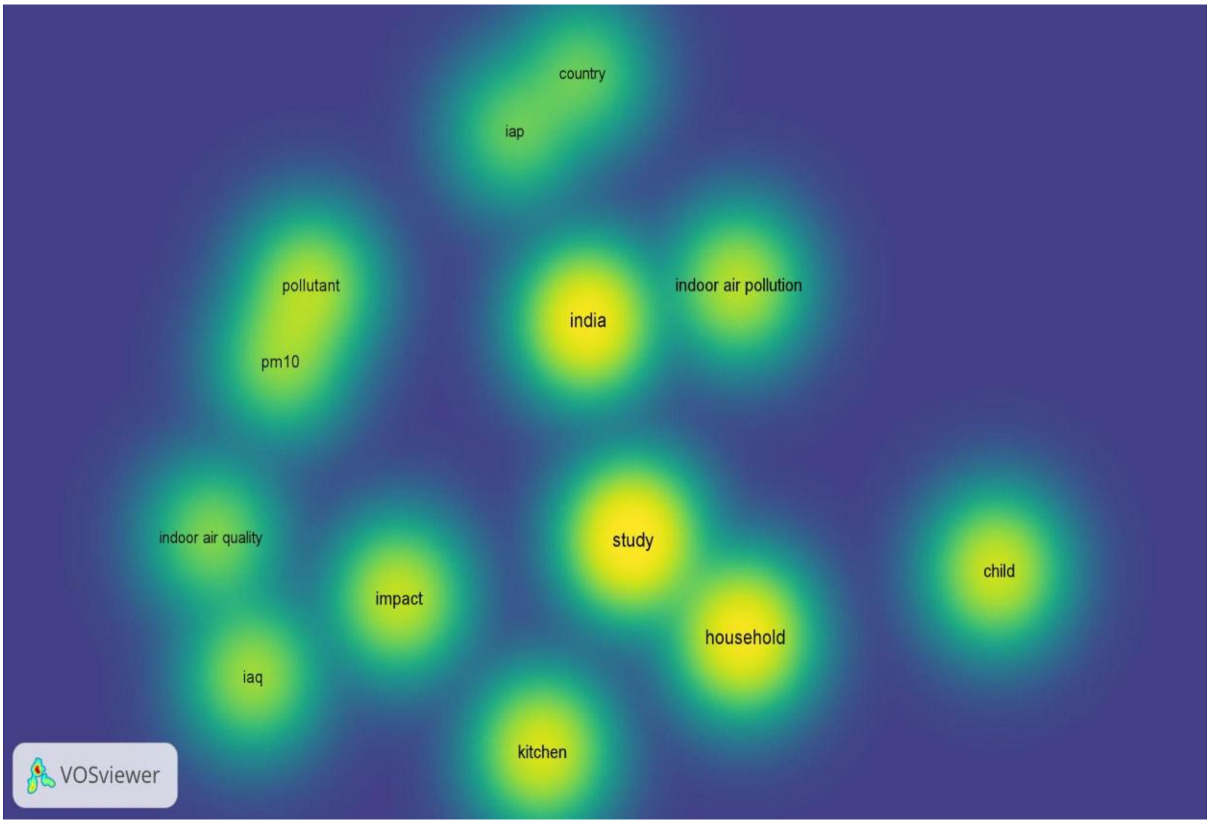

Figure 2b: Identification of hotspots of study area/topic.

RESULTS AND DISCUSSION

Recent research in India has been reviewed and presented with an updated overview of the sensors and applications used to monitor indoor and outdoor air quality in real-time. We also offer suggestions for how to improve the quality of air quality monitoring devices that use low-cost sensors.

3.1. Air quality studies in India

Source apportionment of Indoor air pollution sources i.e., incense sticks, mosquito coils, cigarettes, and charcoal were studied. Cooking fuel charcoal is burned in the largest quantities, followed by mosquito coils, incense sticks and drop, and lastly cigarettes (Kaur et al., 2020). Multitude of studies involving Indoor ventilation, effectiveness of air filters in reducing exposure to fine particulate matter (PM2.5), effectiveness of HVAC systems, air quality of sedan cars, exposure in cooking, heating, smoking and hair dressing related exposure were studied using low-cost sensors. Further, development of integrated environment chambers for multipollutant monitoring, machine learning model development and sensor activation were the focus of the low-cost sensors. Interestingly only specific choice of sensors for specific purpose such as Relative humidity and temperature (DHT11,22), Particulate matter (Sharp GP2Y1010AU0F,PMSA003 and SDS011), and gaseous pollutants (MQ series for CO, CO_2, NO, NO_2, O_3, and SO_2) were employed in 90% of the studies (Palanivel Raja and Manirathinem, 2009; Sivasankari et al., 2016;Parmar et al., 2017; Kiruthika and Umamakeswari, 2017; Kumar and Jasuja, 2017;Sharma et al., 2017; Shitole et al., 2018; Sarjerao and Prakasarao, 2018; Boppana et al., 2019; Sai et al., 2020; Sahoo et al., 2019; Kaur et al., 2020; Gupta et al., 2020; Jyothi and Shanmugasundaram, 2022; Sharma et al ., 2023). It is important to note that 68% of the indoor air quality monitoring systems are based on Arduino, 15% of the systems use Internet of Things, and WSN architectures represent 17%. Metal oxide semiconductor (MOS) and Electrochemical (EC) were majorly (95%) used in low-cost air quality monitoring choices for gaseous pollutant monitoring by the individuals in India. In the case of particulate sensor, the most prominent choice of the principle was the light scattering method (PMS, Nova SDS Series and Shinyei PPD Series). Indoor and outdoor air quality was studied together only in Chennai and Lucknow to assess the nexus of indoor and outdoor air quality during cooking hours.

Sensors	Parameter	Architecture	Micro controller Unit	Data Display/ access	Test conducted	Standard method used to validate	Reference
DHT11	Temperature and humidity	IoT	Raspberry Pi, Arduino Uno	Application	Environment monitoring (majorly Indoor) and integration with air quality sensor/environmental chamber	Not validated	Sivasankari et al., 2016; Sharma et al., 2017; Shitole et al., 2018; Saha et al., 2018; Sarjerao and Prakasarao, 2018; Zhang and Srinivasan, 2020; Saini et al., 2020; Jyothi and Shanmugam Sundaram, 2022; Sharma et al., 2023; Kumar and Jasuja, 2017; Urku and Agrawal, 2019
DHT22	Temperature and humidity	IoT	Raspberry Pi	Application	Plant growth monitoring	Not validated	Shitole et al.,2018
Sharp GP2Y1010 AU0F	$PM_{2.5}$	IoT	Arduino Uno	Mobile application (Blynk platform)	IOT based monitoring for indoor and outdoor quality	Not validated	Curto et al.,2018; Kaur et al., 2020
MQ135 sensor	Ammonia, benzene, smoke, carbon dioxide and toxic gases	IoT	Arduino Uno	Mobile application (Blynk platform)	Monitoring of indoor air quality (house, lab) and gas leak detection. IoT based data integration	Not validated	Sharma et al.,2017; Kiruthika and Umamakeswari,2017; Sarjerao and Prakasharao,2018; Parmar et al.,2018; Gupta et al.,2020; Panicker et al.,2020
MQ-4, MQ-5, MQ-6, MQ-7, MQ-9	Carbon monoxide	IoT	Arduino Uno	GSM and M2M communication to display in mobile	Mobile application, cloud service, personal monitoring and environmental chamber development (outdoor), HVAC, IoT	Not validated	Kumar et al.,2017: Sharma et al.,2017; Kiruthika and Umamakeswari,2017; Sarjerao and Prakasharao,2018; Parmar et al.,2018; Gupta et al.,2020; Panicker et al.,2020
EL-USB-CO	Carbon monoxide	-	-	-	Wood chamber experiments	QTrak	Curto et al.,2018

DSM501A	PM greater than 1	Losant based IoT	Mangoose OS based ESP-32	MQTT protocol in Losant application	IoT, indoor air sensing, testing of sensor module	Not validated	Boppanna et al.,2019;Kumar and Jasuja,2017
COZIR GC-0010	Carbon dioxide	Bluetooth	Sensodrone	Smartphone	For developing mobile sensing device for vehicle indoor air quality	Not validated	Lohani and Acharya,2016
TGS2600	methane, hydrogen, carbon monoxide, iso-butane, and ethanol	IoT	Arduino Uno	GSM and M2M communication to display in mobile	For developing indoor air quality sensor	Not validated	Yogalakshmi et al.,2015
TGS2602	hydrogen, ammonia, toluene, and ethanol	IoT	Arduino Uno	GSM and M2M communication to display in mobile	For developing indoor air quality sensor	Not validated	Yogalakshmi et al.,2015
MQ-138	VOC (ethanol), carbon monoxide and Carbon dioxide	IoT	Arduino Uno	GSM and M2M communication to display in mobile	Development of indoor air quality sensor using Machine to Machine communication technology	Not validated	Kumar et al.,2017
MQ131	Carbon monoxide, Ozone	Losant based IoT	Mangoose OS based ESP-32	MQTT protocol in Losant application	IoT, indoor air sensing, testing of sensor module	Not validated	Boppanna et al.,2019
Mics 2714, MiCS-6814	NO_2 CO, NOx, ethanol, ammonia, and methane	IoT	Raspberry Pi	IP Address on Web	Indoor air quality alert system	Not validated	Sivasankari et al.,2016.

MH-Z16 and MG811	CO_2	IoT	Raspberry Pi	IP Address on Web	Indoor air quality alert system	Not validated	Sivasankari et al.,2016.
SDS011	PM	IoT	Node-ESP32	Virtuino app and Thing speak platform	Development of integrated environment chamber	Not validated	Veeramanikandasamy et al.,2020
Airveda	PM,CO_2	IoT	NA	Application	Machine learning and laboratory monitoring	Beta attenuation Monitor, CO_2 NDIR sensor reference grade NABL calibrated instruments	Dutta and Roy,2021
Air sense	PM	IoT	NA	Application	To monitor indoor air quality in laboratory	Beta attenuation Monitor, CO_2 NDIR sensor reference grade NABL calibrated instruments	Dutta and Roy,2021
PMSA003	PM	IoT	Raspberry Pi3 B+	Application in mobile (Thinkspeak platform)	HVAC in class room	Comparison with field data from continuous monitoring station (NAMP)	Anitha and Sutha Kumar,2023
SPEC DGS-SO2 Alphasense NO2-B43F, SPEC 3SP_NO2_5FP, Plant owner	SO_2, NO_2, PM	-	-	-	For monitoring air quality in campus and laboratory	Reference grade instruments	Lambey and Prasad,2022

PMS7003, Prana Air PAS-OUT-01 (both based on light scattering principle), and Met One Instruments BAM 1020							

Table-1: summery of different sensor and its type used

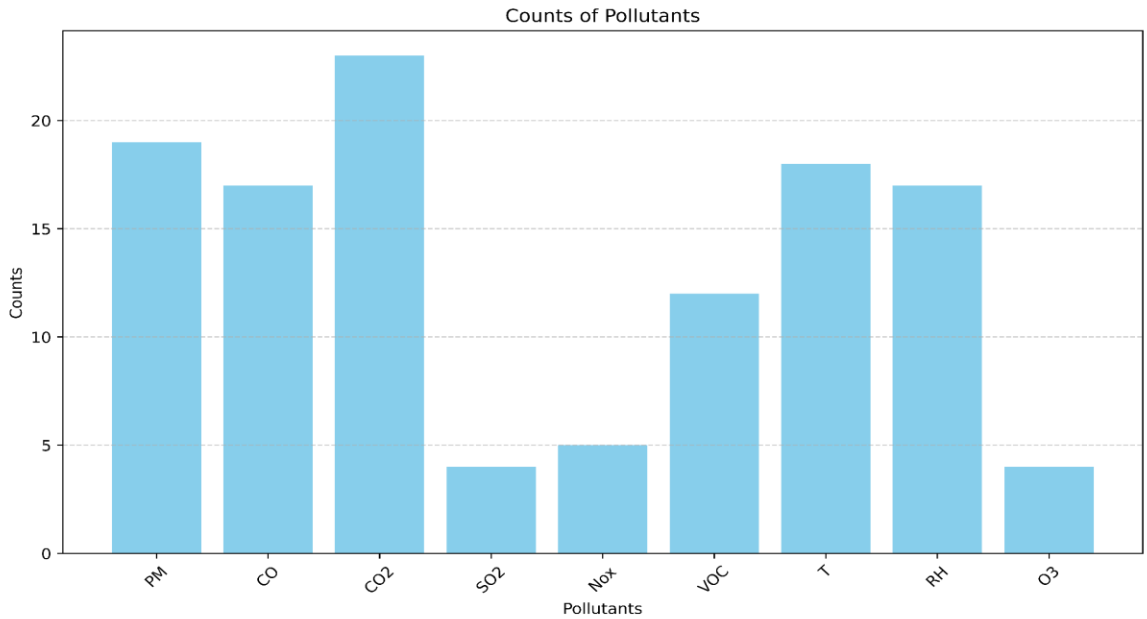

Figure 3: Counts of a pollutant monitored using sensor in India.

3.2. Problems with installing low-cost sensors:

Although monitoring air quality with inexpensive sensors is an intriguing alternative to traditional monitoring approaches, perspectives on air quality monitoring with sensors range from overly hopeful to dismissing the results as inapplicable. There are several reasons behind these conflicts over the usage of low-cost sensors in the air quality monitoring network. Firstly, Low-cost sensors may exhibit less precision when compared to established reference devices. The reliability of data can be affected by the calibration, cross-sensitivity, and stability of sensors (Borrego and Costa, 2017). The calibration and maintenance of inexpensive sensors present difficulties, and these sensors may experience drift over time. Another obstacle to obtaining accurate and dependable data is the absence of reliable calibration techniques. To validate sensors, there are currently only a few options, such as correlating results to reference methods and ensuring measurement reproducibility by using many identical or comparable sensors (Bucek et al,2021).

The prediction and forecasting of indoor air pollution heavily rely on machine learning and data analysis, necessitating a high level of detail or spatial resolution that can only be achieved using multiple or large volumes of sensors, which is not possible in many situations, especially for a highly diversified country like India (Sharma et al., 2021). Despite the comparatively low initial cost of deployment, manpower costs for processing and maintaining the network will probably soon outweigh the hardware costs for a sensor network. It is essential to include additional hardware needs, setup and installation expenses, and field calibration charges in the overall budget. Thus, in addition to the advancement of sensor technology, the future of sensor networks for air quality applications depends on the availability of reasonably priced and easily accessible services for data processing and sensor-network maintenance (Garcia et al.,2022).
Harmonizing data from different low-cost sensors poses a significant challenge. Ensuring data consistency across various sources is crucial for making accurate comparisons and informed policy choices (Giordano et al., 2021). Enhancing source compliance monitoring is of utmost importance in developing countries. Furthermore, the implementation of personal exposure monitoring on a large scale has been hindered by the need for study volunteers who are willing and dedicated, unlike the ease of stationary deployment (Sousan et al., 2016).

3.3. Air quality projects in India

The National Clean Air Programme (NCAP) and the National Air Quality Monitoring Programme (NAMP) are two of India's most prominent initiatives for tracking national ambient air pollution levels. These initiatives cover almost all of the nation's major cities and urban areas. However, there is a tremendous need to expand the air quality monitoring network to increase spatial coverage and to track exposure at the household and individual levels, considering the extent of health impacts produced by air pollution. Currently, India is home to a handful of monitoring programs that rely on low-cost sensors. Sensor-based Wireless Air Quality Monitoring Network (SWAQMN) is a collaborative project spearheaded by CSIR-NEERI, aiming to address the limitations of existing air quality monitoring systems in Delhi. SWAQMN primarily uses poll drone sensors, a low-cost sensor developed by OIZOM. CHAI (Cardiovascular Health Effects of Air Pollution in Telangana, India) project was a European Research Council-funded observational cohort study conducted in Telangana. The study was designed to understand exposure and personal exposure to particles and to quantify the association between particles and markers of atherosclerosis.
Standardized techniques were developed and deployed in two NGO-led programs in India and one in Mexico known as The Household Energy and Health Project. The Household Energy and Health Project conducted monitoring and evaluation of improved cookstove programs. The study emphasizes practical actions to address indoor air quality (Smith et al.,2007).

The Tamil Nadu Air Pollution and Health Effects Study (TAPHE-2) aims to evaluate the relationship between air pollution and birth outcomes in a rural-urban cohort of 300 pregnant women during the COVID-19 period in Chennai using low-cost sensors. (Puttaswamy et al.,2022).
An awareness campaign was initiated by Shell Organization and Enviropig International (a social venture in the US) in 2008 to promote healthier options. Organizing theatres and demonstrations in social settings was a key method used to disseminate knowledge (Patnaik, Tripathi, & Jain, 2019).An enterprise called the National Biomass Cookstove Initiative (NBCI) was established by the Ministry of New and Renewable Energy on December 2nd, 2009, to encourage and develop improved cookstoves.
ATMAN (Advanced Technology for Mitigating Air Pollution) is a Centre of Excellence at IIT Kanpur. It focuses on revolutionizing air quality monitoring through low-cost sensor-based indigenous technologies. The AMRIT project aims to establish a dense Sensor Ambient Air Quality Monitor (SAAQM) network(Home - Centre of Excellence - ATMAN (urbansciences.in).This network comprises 1,400 nodes distributed across rural regions in Bihar and Uttar Pradesh.ATMAN collaborates with organizations like the Clean Air Fund, Uttar Pradesh Pollution Control Board (UPPCB), and Lucknow Municipal Corporation. So far low-cost sensors have been strategically deployed across rural areas in the states of Bihar and Uttar Pradesh. ATMAN has the following objectives to produce Next Gen Atma-Nirbhar PM Sensors and Use the Air Quality sensors for Real-Time Source Attribution and also use AI/ML for nation-wide AQ monitoring networks.

Streaming Analytics over Temporal Variables from Air quality Monitoring (SATVAM) initiative was started in India in 2017 to develop tools, technologies, and architectures for deploying and studying air quality monitoring at city-wide scales with finer spatial and temporal granularity (Prof. Sachchida Nand Tripathi (sntripathi.in).The project leverages IoT (Internet of Things) technologies, including low-cost sensing, energy harvesting, low-power communication networks, and edge analytics. Maharashtra Pollution Control Board collaborated with SATVAM project and installed 15 low-cost sensors for continuous monitoring for field evaluation of sensing capability which became highly successful. Hence, approximately 100 air quality monitors have been set up in 6 locations of India (Chennai:40, Lucknow:71, Mumbai:15, Kanpur:30, Jaipur:40, and Delhi each covering 12 districts with different levels of PMUY beneficiaries, ranging from the highest to the lowest density (Sahu et al.,2021).

While countries like the United Kingdom (ARUN network), United States (USEPA's AQMN), and Europe (EEA) boast extensive and well-functioning air quality monitoring networks, these systems come with hefty costs and require significant space for installation. This poses a major challenge for densely populated megacities in low- and middle-income countries (LMICs).

Over two-thirds (11 out of 17) of large air quality monitoring projects across the globe have received government funding through competitive grants. Among large-scale projects, a significant portion (30%) are commercially or crowd-funded, suggesting a move away from solely government-controlled, regulatory monitoring. This new approach might involve diverse stakeholders and provide data beyond regulatory needs. In the case of India, crowd funded, or individual funded studies dominate compared to government projects. This scenario is due to the following reasons.

The government might prioritize funding well-established, high-accuracy monitoring stations with a proven track record. Low-cost sensors are a relatively new technology, and their data quality can be a concern. The best examples were SATVAM, ATMAN and SAAQM.

Low-cost sensors from various manufacturers might require standardization and regular calibration to ensure consistent measurements across the network. This can be a logistical challenge. Since there is no protocol available to validate low-cost sensor networks in India.

Even low-cost sensors require an investment for deployment and maintenance. The government might have limited budgets allocated for air quality monitoring, and established stations might take priority.

Need for Protocols

Particulate Matter regulations in the US and EU rely on reference methodologies, such as gravimetric examination of filters at certain temperatures and RH. It is challenging to calibrate low-cost sensors using reference methods, as gravimetric analysis is a manual, offline procedure with limited time resolution (24-h integrated measurements). Furthermore, gravimetric reference methods do not evaluate the time-resolution improvements of low-cost PM sensors. The Next-best option is to employ equivalent reference methods (eRMs) for hourly PM mass concentrations with improved time-resolution. Beta attenuation monitors (BAM) and tapered element oscillating microbalances (TEOM) are the most prevalent eRMs, and this light scattering equipment fulfill comparison standards for 24 h averaging periods, but provide higher time resolutions than daily observations (Giordano et al.,2021). USEPA provides guidelines for evaluation of Air sensor performance in comparison with the regulatory grade equipment. USEPA updated the precision of the following sensors using R2 value. An R2 value of 1 indicates complete correlation with the reference monitor, whereas an R2 value of 0 indicates no connection with the reference monitor.

Table 2 Calibration techniques and sensor adopted by USEPA for particulate matter.

S.No	Parameter	Air quality sensor	R2 value	Reference monitor
1	$PM_{2.5}$	Alphasense OPC N2	0.007	GRIMM EDM 180 FEM PM2.5 Monitor
2	$PM_{2.5}$	Shinyei	0.60	MetOne BAM 1020 FEM PM2.5 Monitor

3	$PM_{2.5}$	AirBeam	0.66	MetOne BAM 1020 FEM PM2.5 Monitor
4	$PM_{2.5}$	Dylos	0.67	MetOne BAM 1020 FEM PM2.5 Monitor
5	$PM_{2.5}$	MetOne	0.41	MetOne BAM 1020 FEM PM2.5 Monitor
6	$PM_{2.5}$	Air Quality Egg	0.40	MetOne BAM 1020 FEM PM2.5 Monitor
7	$PM_{2.5}$	Cairpol CairClip PM - prototype	0.06	Grimm Model EDM180 PM2.5 monitor
8	$PM_{2.5}$	Airviz Speck v2	0.01	Grimm Model EDM180 PM2.5 monitor
9	$PM_{2.5}$	Dylos DC1100	0.55	Grimm Model EDM180 PM2.5 monitor
10	$PM_{2.5}$	Met One Model 831	0.77	Grimm Model EDM180 PM2.5 monitor
11	$PM_{2.5}$	RTI MicroPEM	0.72	Grimm Model EDM180 PM2.5 monitor
12	$PM_{2.5}$	Shinyei PMS-SYS-1	0.15	Grimm Model EDM180 PM2.5 monitor

Table 3 Calibration techniques and sensor adopted by USEPA for gaseous pollutant.

S.No	Parameter	Air quality sensor	R2 value	Reference monitor
1	Ozone	AQMesh	0.45	Thermo Fisher Scientific FEM 49I ozone monitor
2	Ozone	AQMesh	0.94	Thermo Fisher Scientific FEM 49I ozone monitor
3	Ozone	WT-SU1 Dynamo	0.95	Thermo Fisher Scientific FEM 49I ozone monitor
4	Ozone	CairClip	1.00	Thermo Fisher Scientific FEM 49I ozone monitor
5	Ozone	Aeroqual SM50	0.97	Thermo Fisher Scientific FEM 49I ozone monitor
6	Nitrogen oxide	AQMesh	0.32	Thermo Fisher Scientific FEM 42C nitrogen dioxide monitor

7	Nitrogen oxide	Air Quality Egg	-0.22	Thermo Fisher Scientific FEM 42C nitrogen dioxide monitor
8	Nitrogen oxide	Air Casting	0.98	Thermo Fisher Scientific FEM 42C nitrogen dioxide monitor
9	Nitrogen oxide	Platypus	0.80	Thermo Fisher Scientific FEM 42C nitrogen dioxide monitor
10	Nitrogen oxide	CitiSense	0.98	Thermo Fisher Scientific FEM 42C nitrogen dioxide monitor
11	Nitrogen oxide	U-Pod	0.88	Thermo Fisher Scientific FEM 42C nitrogen dioxide monitor

The Protocol of Evaluation and Calibration of Low-Cost Gas Sensors for the Monitoring of Air Pollution is a significant research project conducted by the European Metrology Research Programme (EURAMET). The project, known as Metrology for Chemical Pollutants in Air (MACPoll), focuses on evaluating and calibrating low-cost gas and particulate sensors used for air quality monitoring. These sensors are considered emerging measuring devices for "indicative measurements" regulated in the Air Quality Directive. Compared to reference measurements, these gas sensors offer the advantage of lower cost for air pollution monitoring. The protocol defines three sensor categories:
Class 1: Measuring devices consistent with the Air Quality Directive (AQD) and formally evaluating uncertainty.
Class 2: Measuring devices consistent with the AQD but with less stringent uncertainty requirements.
Class 3: Associated with AQD but not formally evaluated for uncertainty.
In zones where the upper assessment threshold (UAT) is not exceeded, the Air Quality Directive (AQD) allows indicative measurements. In places where the UAT is exceeded, indicative measures reduce minimum reference measurements by 50%. The AQD does not specify an indicative method, but it requires these sensors to fulfill a lower data quality objective (DQO) than reference methods. The MACPoll project developed a gas sensor evaluation mechanism. Sensor identification, model, test board, power supply, data collecting, and other specifics are in the protocol. Evaluation compares sensor performance to an AQD limit or goal value, considering averaging time and micro-environment (Spinelle et al.,2013).

Policy interventions and status

NBCI's Unnat Chulha Abhiyan Programme was created in 2014 to enhance biomass cookstoves, save women and children time, and reduce BC emissions. The 12th plan of the Unnat Chulha Abhiyan aims to distribute 2.75 million improved cookstoves/chulhas. Rural households, Midday Meal (MDM) Scheme kitchens, and small businesses (roadside dhabas, small motels, and restaurants) use biomass for cooking (Unnat Chulha Abhiyan — Vikaspedia). 36,940 family-type and 849 community-type upgraded cookstoves were supplied under Unnat Chulha Abhiyan (Ranjan and Bandra,2019). Only about 2% of modified chulhas have been supplied, a significantly low number considering that over 80% of rural families still use conventional fuels for cooking.

The Ministry of Petroleum and Natural Gas (MOPNG) launched the "Pradhan Mantri Ujjwala Yojana" (PMUY) in May 2016 to provide clean cooking fuel like LPG to rural and impoverished households that used firewood, coal, cow-dung cakes, etc. since traditional cooking fuels harmed rural women and the environment (https://www.pmuy.gov.in/about.html). After the introduction of the scheme, the LPG consumption has increased from 1.4Mt to 1.7Mt since 3.5 crore new connections were disbursed (the goal is to disburse 5 crore connections). The current target has risen from 5 crore to 8 crore. However, LPG use among newer consumers, particularly PMUY beneficiaries, is lower than before, suggesting inconsistent use of PMUY connections. The price increase of even subsidized LPG, which rose by 12% between April and December 2017, may worsen this situation (Dabadge, 2018). The government has spent over 128 billion in subsidies, and almost 70% of the PMUY beneficiaries have taken loans from Oil Manufacturing Companies (OMCs). Furthermore, rural households having five members couldn't afford 14.2 kg (the required amount to cook food with LPG as primary fuel) to take loans resulting in a burden on the family (Singh et al,2020). Ujjwala Yojana 2.0 has completed a 9.6 crore disbursement of connection as of March 2022 and planning to extend the target (https://www.pmuy.gov.in/about.html). However, more work is needed to use LPG for cooking consistently. The social, economic, and health benefits of household air pollution reduction can be fully realized by addressing the ongoing hurdles of translating initial liquefied petroleum gas adoption to sustained adoption and limited desertion of traditional fuels.

Sector-specific interventions have been planned for cities to curb ambient air pollution through an ambitious national clean air program. The NCAP aims to achieve a 20 to 30% reduction in Particulate Matter concentration nationwide by 2024. NCAP is operational in 132 cities nationwide. In the program, during 2018 NCAP introduced 122 nonattainment cities and identified action points across all states of India. These action points are based on emission categories whereby most of the emission is articulated to vehicular, road dust, and industries accounting for 50-70% of total emission. An average emission scenario outside the city airsheds of the states in India as follows the transport (18.07%), dust (15.14%), industry (10.48%), residential (9.84%), diesel generator (3.66%), and brick manufacturing (2.18%) (Guttikunda et al.,2019b). Delhi has the most action plans, including converting bus and para-transit vehicles to compressed natural gas, moving brick kilns and smaller industrial clusters to the outskirts, introducing Bharat-VI fuel two years earlier than the rest of the nation, approving the graded responsibility action plan (GRAP) in severe episodes, and piloting the odd-even scheme in winter (Ganguly et al.,2020). Delhi action plans were planned to replicate. Only Uttar Pradesh, Gujarat, Andhra Pradesh, and Maharashtra have shown progress in implementation of clean air action plans(https://pib.gov.in/PressReleseDetailm.aspx?PRID=1907272). However, due to a lack of regional coordination, lack of institutional and urban local cooperation towards the authority (pollution control plans), and lack of source apportionment studies (only 25% of the total states have source apportionment studies) thus unable to set specific emission reduction plans and lack of infrastructural planning all these factors collectively caused the action plans to failure in most of the cities (Ganguly et al.,2020).

The current aim of the Ministry of Environment, Forest and Climate Change for NCAP is that it aims to reduce PM10 levels by 40% or meet national requirements (60 micrograms/cubic meter) in 131 cities in 24 states by 2025-26. States/UTs have also been asked to access Union Government Scheme convergence funds to improve air quality. The schemes such as FAME-II/EV mobility, SATAT, Electric mobility, National Afforestation and Eco-developmentBoard(https://www.indiascienceandtechnology.gov.in/organisationenvironment/national-afforestation-and-eco-development-board-naeb), Flue-gas Desulfurization and pollution control measures (National mission on use of Biomass), phasing out of old vehicles and implementation of vehicle registering policy were launched for targeted 131 cities to improve the air quality.

Specifically, it is important to discuss that the new action plan of NCAP (2024) aims to implement the following (a) increase CAAQMS to 1000 stations. (b) Add 50 rural areas with stations to the monitoring network. (c) update the 2003 ambient monitoring rules to allow low-cost sensors and research-grade monitoring equipment, including a new certification mechanism. (d) Create a 10-city super monitoring network (Venkataraman et al., 2020). (e) Encourage indoor air pollution monitoring programs that focus on domestic fuel burning and (f) create an air information center. Awareness initiatives distribute monitoring data and short-term air quality forecasts.

RECOMMENDATIONS

1. Limited studies on specific pollutants: While some studies have examined general indoor air quality in India, there is a lack of research focusing on specific pollutants that may pose significant risks to human health, such as volatile organic compounds, particulate matter, formaldehyde, and carbon monoxide.

2. Measurement techniques and standardization: Standardized methods of measuring indoor air quality are necessary in India. Comparing and drawing meaningful conclusions from the available studies is made

more challenging using different methods and equipment. Furthermore, Indian legislation and standards for indoor air quality monitoring are nonexistent.
3. Long-term health effects: The rapid health impacts of short-term exposure to indoor air pollution have been the subject of numerous studies in India. On the other hand, studies looking at the impact of indoor air pollution on health over the long term are scarce.
4. Impact of regional and cultural practices: Indoor air quality can be impacted by the numerous cultural practices and regional traditions of India. We need further studies to compare the health impacts of indoor air pollution across regions of India and find out how various practices—like indoor smoking, using traditional fuels, and cooking methods—contribute.
5. Effectiveness of mitigation strategies: Although there have been studies looking at the efficacy of specific mitigation measures like ventilation systems and air purifiers, there is a dearth of studies comparing the efficacy of diverse mitigation strategies across different locations and settings in India.

CONCLUSION

A systematic review of indoor and outdoor air quality monitoring using low-cost sensors in India is conducted spanning over two decades. Most of the low-cost sensors were employed as a qualitative scale to monitor particulate matter and gaseous pollutants in the indoor during various activities (cooking, cleaning, source apportionment, and HVAC). While outdoor monitoring is majorly for particulate matter for validation and testing against conventional air quality monitors. The individual sensor-based monitoring is high compared to government funded monitoring programs in India. However, there is no calibration or validation was carried out by Individuals monitoring indoor air quality in India. Further, few studies explored machine learning and statistical model development based on big data produced by low-cost sensors. The policy interventions were successful in delivering LPG connections to prevent emissions from cooking in India. In case of outdoor air quality there were many policy interventions taken in major cities like Delhi, Lucknow and Chennai whereby the expected drop in air quality is not achieved. To conclude, the increase in investment towards development and calibration of low-cost sensor in conjunction with the reference grade monitor is suggested. Further, framing policies for individuals who are performing research in low cost sensor development and deployment and also enactment of awareness programs regarding low-cost sensor monitoring will pave the way for achieving national determined contribution goals of India.

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CONFLICT OF INTEREST

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