International Journal of Environmental Sciences
ISSN: 2229-7359
Vol. 11 No. 17s, 2025
https://www.theaspd.com/ijes.php

Developing An Integrated Framework Of Advanced Monitoring Technologies For Enhancing Environmental Sustainability And Policy Effectiveness: A Systematic Literature Review

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ABSTRACT
This review explores recent advancements in environmental monitoring technologies, including sensors, IoT, remote sensing, and AI, emphasizing their potential to enhance environmental sustainability and inform policy decisions. It synthesizes developments across various environmental sectors such as air, water, soil, and biodiversity that highlighting their applications, benefits, and existing challenges such as accuracy, scalability, and policy barriers. The paper advocates for an integrated monitoring framework that combines multiple technological approaches, supported by stakeholder collaboration and policy incentives. Future directions focus on technological innovations and cross-sectoral governance necessary to address complex environmental challenges effectively. This comprehensive overview underscores the transformative potential of modern monitoring systems in shaping smarter, more responsive environmental policies.

Keywords: *environmental monitoring, sensors, remote sensing, artificial intelligence, policy framework, sustainability, integrated systems.*

INTRODUCTION

The rapid evolution of environmental monitoring technologies has become increasingly vital for sustainable development. Effective monitoring supports key areas such as resource management, pollution control, biodiversity conservation, and climate change mitigation. Reliable data is crucial for stakeholders including policymakers, scientists, and communities to make informed decisions that balance development with ecological sustainability.

Early advancements in environmental monitoring centred on sensor systems that measured key parameters like air quality, water purity, and soil health. For instance, Lun et al. (2024) demonstrated how a multi-sensor system using BME680, SCD30, PMS7003, and BH1750, integrated with Wi-Fi modules, enabled scalable indoor environmental monitoring and real-time alerts. Similar innovations in low-cost sensors for coastal and water quality monitoring have enabled deployment in resource-limited regions (Korku et al., 2022; Dhall et al., 2021).

Sensor technologies have further advanced with the use of hybrid nanomaterials, enhancing sensitivity and durability. Dhall et al. (2021) reviewed the role of graphene, carbon nanotubes, and metal oxide nanoparticles in detecting key air pollutants. Yet, accurate calibration remains a concern which by Jiang et al. (2022) highlighted a new system for soil respiration chambers, underscoring the importance of precise calibration.

Remote sensing technologies, especially satellite-based systems, have significantly expanded environmental monitoring capacity. Tools such as EMI and EMI-NL offer high-resolution data on ozone and NO_2 using Differential Optical Absorption Spectroscopy (DOAS), validated against ground measurements (Yang et al., 2022; Qian et al., 2021). When integrated with GIS, these tools enhance assessments of urban growth, deforestation, and land degradation (Regina et al., 2023; Estoque et al., 2021).

Artificial Intelligence (AI) and Machine Learning (ML) are now central to processing complex environmental datasets.

Hamza et al. (2022) combined Hadoop MapReduce with hybrid ARIMA-neural network models for accurate air pollution forecasting. Similarly, Rawashdeh et al. (2024) demonstrated how AI-based classifiers improve detection accuracy and resource allocation. These tools enable real-time decision support systems and interactive dashboards for policy-making.

Nonetheless, technical and systemic barriers persist. Sensor reliability can be compromised by environmental stressors, making calibration and maintenance critical (Jiang et al., 2022; Zhao et al., 2022). Integrating diverse datasets from ground sensors, satellites, and other sources requires advanced data fusion techniques to avoid inconsistencies (Regina et al., 2023).

Policy limitations further hinder progress. There is a lack of standardized protocols and clear regulations around data sharing and privacy (Li et al., 2023; Zulkifli et al., 2022). Socioeconomic constraints such as infrastructure costs and technical expertise and pose barriers, particularly in low-resource contexts. As noted by Ali et al. (2022) and Cing & Mansor (2023), targeted policies and capacity-building initiatives are needed to support widespread technology adoption.

To address these challenges, integrated monitoring frameworks are being developed. These combine sensors, remote sensing, and AI into unified platforms with real-time, high-resolution capabilities. Lun et al. (2024) emphasized the importance of feedback mechanisms in these systems, enabling adaptive policymaking. Successful implementations depend on stakeholder collaboration, robust governance, and alignment with existing systems.

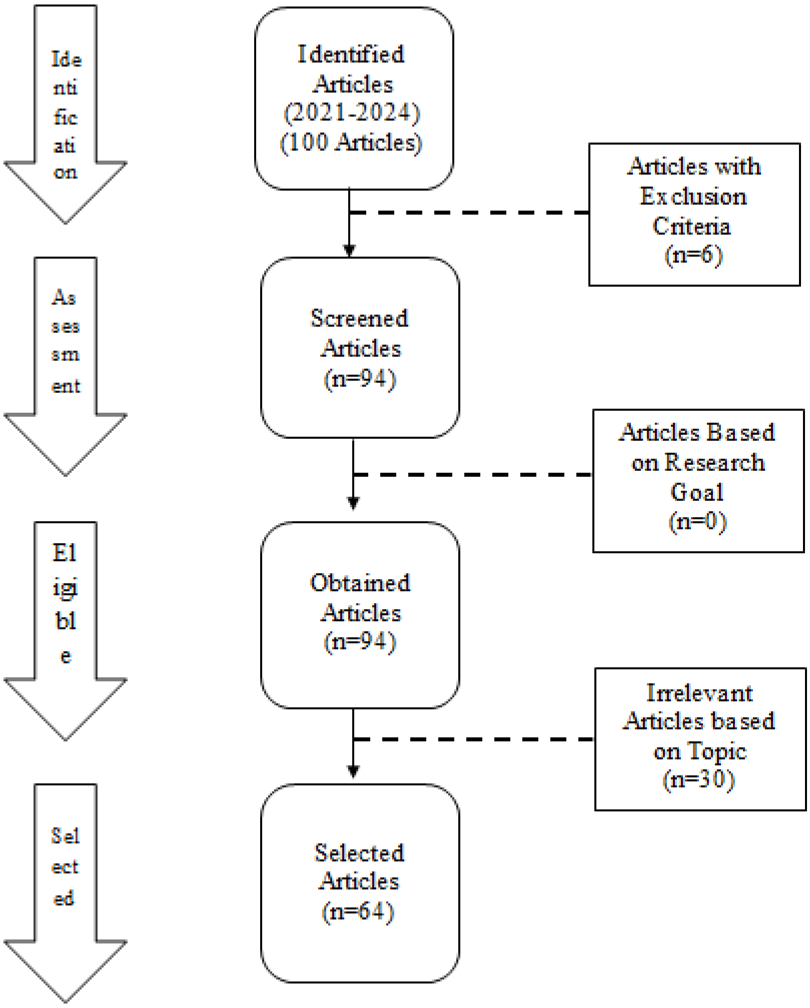
Future efforts should prioritize self-calibrating, autonomous sensors and virtual testing platforms like Alpha Mobile Sensing (Zhou et al., 2023). Effective digital governance and cross-sector collaboration are essential to ensure innovation and data transparency. Multidisciplinary engagement from environmental science and engineering to policy and social studies will be crucial to tackling complex sustainability issues.

In conclusion, while environmental monitoring technologies have made notable progress, realizing their full potential requires addressing calibration, integration, regulatory, and socioeconomic barriers. Sustained research, innovation, and inclusive policies will pave the way toward smarter, more sustainable environmental management systems.

MATERIALS AND METHODS

This study is a Systematic Literature Review which focuses on exploring Developing an Integrated Framework of Advanced Monitoring Technologies for Enhancing Environmental Sustainability and Policy Effectiveness. The method used in this study is Preferred Reporting Items for Systematic Reviews & Meta-Analysis (PRISMA). The selected articles used by researchers in this study had inclusion criteria, namely research articles, publication year range 2021-2024, journal impact quartile Q1-Q3, and in English.

Data collection techniques were carried out by reviewing studies that were included in the inclusion criteria. The study search was carried out using the keywords "Environmental Monitoring" via Mendeley Reference Manager. Using the PRISMA method, researchers have found a total of 100 related articles.



RESULTS AND DISCUSSION

From the results of the study, there were 64selected pieces of literature obtained from several literatures regarding environmental monitoring in various countries such as China, Brazil, USA, India, Indonesia, Sri Lanka, Kazakhstan, Malaysia, Saudi Arabia, UAE, Kazakhstan and Africa.

Table 1: Relevant Research Summary

S. No.	Researcher and Research Year	Title of Research	Result
1	Lun Min Shih et al. (2024)	Design and Evaluation of Wireless DYU Air Box for Environment-Monitoring IoT System on Da-Yeh University Campus	The DYU Air Box accurately monitors indoor campus environments, offers automatic alarms, and provides stakeholders with accessible environmental data.
2	Tania Septi Anggraini et al. (2024)	Machine Learning-Based Global Air Quality Index Development Using Remote Sensing and Ground-Based Stations	Multiple models outperform single models in accuracy, demonstrating that incorporating socioeconomic and environmental data improves air quality estimates, especially in areas lacking monitoring stations.

3	Sihan Zhang et al. (2022)	Does Improvement of Environmental Information Transparency Boost Firms' Green Innovation? Evidence From the Air Quality Monitoring and Disclosure Program in China.	The program boosted firms' green innovation, particularly in green patent applications, driven by local regulations and public attention, with stronger effects in state-owned and high-polluting industries.
4	Nasir Mahmood et al. (2022)	Role of Environmental Regulations and Eco-Innovation in Energy Structure Transition for Green Growth: Evidence from OECD.	Empirical findings support that environmental regulations drive eco-innovations and green growth, endorsing the double dividend (DD) hypothesis. The study recommends promoting ecotaxes and eco-innovations in OECD countries and sharing these practices with developing nations to support sustainable development.
5	Eliot Chatton et al. (2021)	Innovative Instrument for The Field Continuous Monitoring of Dissolved Gases in Environmental Studies.	MIMS technology provides high-frequency measurements of multiple dissolved gases in the field, offering a valuable tool for environmental studies.
6	Eli Korku Kpobi et al. (2022)	Development of a Raspberry Pi–Based Remote Station Prototype for Coastal Environment Monitoring.	The low-cost equipment demonstrated high efficiency and accuracy, with sea surface temperature data matching satellite readings and strong correlations in atmospheric data with standard stations. Regression analysis enhanced accuracy, highlighting its potential for affordable environmental monitoring.
7	Regina Marcia Longo et al. (2023)	Identifying Key Indicators for Monitoring Water Environmental Services Payment Programs—A Case Study in Brazil.	The study established key water quality indicators and a monitoring flowchart that emphasizes continuous observation of soil, water, vegetation, microclimate, and socioeconomic conditions. It also promotes systematic data organization to support better understanding and usability for diverse stakeholders.
8	Junjie Jiang et al. (2022)	Study of a Calibration System for Soil Respiration	The study found that unsteady-state flow and steady-

		Measurement Chambers.	state chamber methods produced more accurate results with fewer errors than the unsteady-state nonflow chamber. The flow-meter algorithm was identified as the best calibration system due to its stability, ease of use, and ability to enhance measurement accuracy.
9	Shivani Dhall et al. (2021)	A Review on Environmental Gas Sensors: Materials and Technologies.	The review highlights the investigation of different nanomaterials such as carbon nanotubes, Graphene, metal/metal oxide nanoparticles, two-dimensional nanomaterials, and hybrid nanostructures as sensing materials for environmental gas sensors.
10	Taiping Yang et al. (2022)	Preflight Evaluation of the Environmental Trace Gases Monitoring Instrument with Nadir and Limb Modes (EMI-NL) Based on Measurements of Standard NO2 Sample Gas.	The results confirm the ability of EMI-NL to provide accurate spaceborne monitoring of NO2 globally, with relative errors of spatial pixels generally within a few percentages.
11	Fuying Tang et al. (2022)	Successful Derivation of Absorbing Aerosol Index from the Environmental Trace Gases Monitoring Instrument (EMI).	Identify their finding and write their results. Study carefully. Only use Not Available as a last resort.
12	Manar Ahmed Hamza et al. (2022)	Big Data Analytics with Artificial Intelligence Enabled Environmental Air Pollution Monitoring Framework.	The proposed OAI-AQPC technique showed enhanced prediction performance over recent state-of-the-art techniques, indicating its effectiveness in air quality prediction and classification.
13	Suwari Akhmaddhian et al. (2023)	The Strengthening Government Policies on Mineral and Coal Mining to Achieve Environmental Sustainability in Indonesia, Africa and Germany.	Indonesia's earlier mining laws granted local governments authority over licensing and monitoring, but revoking these policies created a regulatory gap that caused environmental harm. Recently, mining governance in Indonesia, Africa, and Germany has begun shifting toward promoting

			environmental sustainability.
14	Alexandra Jiricka-Pürrer et al. (2021)	Who cares? Don't underestimate the values of SEA monitoring!	Monitoring showed that responsible institutions recognized the benefits of environmental sustainability. Long-term use of Strategic Environmental Assessment (SEA) led to positive learning and greater environmental awareness, while also improving visibility and communication among decision-makers and stakeholders.
15	Shruti Shruti et al. (2021)	Evaluating the Environmental Sustainability of Smart Cities in India: The Design and Application of The Indian Smart City Environmental Sustainability Index.	The analysis shows three cities (Delhi, Allahabad, Bhubaneswar) in the Fair category; two cities (Varanasi, Patna) in the Poor category based on SCESI, indicating varying levels of environmental sustainability.
16	Nurkaidah et al. (2024)	Implementation of Environmental Policies on The Development of a New Capital City in Indonesia.	Implementation faces challenges such as coordination problems; recommendations include implementing accommodative and adaptive policies, routine monitoring and evaluation, close collaboration, and increasing public education and environmental awareness.
17	O. J. Oyebode et al. (2023)	Strategic Monitoring of Groundwater Quality Around Olusosun Landfill in Lagos State for Pollution Reduction and Environmental Sustainability.	Some water parameters such as dissolved oxygen, iron, lead, manganese, and magnesium had concentrations higher than standard limits in some sampling sites; investigations and regular monitoring are recommended.
18	Sareh Rajabi et al. (2022)	Identification and Assessment of Sustainability Performance Indicators for Construction Projects.	The study identified 22 sustainability indicators, highlighting renewable energy and construction site safety as the most important. It aids contractors in selecting relevant indicators during construction.
19	Ridha Ouni & Kashif Saleem (2022)	Framework for Sustainable Wireless Sensor Network	The abstract does not clearly state specific findings or

		Based Environmental Monitoring.	results from the implementation.
20	Keshara De Silva et al. (2022)	Public Sector Accountability to Implement Sustainable Development Goals in Sri Lanka: Influence of Traditional and Non-Traditional Donors.	Environmental degradation remains a continuing issue; deficiencies in governance and accountability threaten the attainment of SDGs, including environmental sustainability.
21	S. Subasinghe et al. (2021)	Monitoring the Impacts of Urbanisation on Environmental Sustainability Using Geospatial Techniques: A Case Study in Colombo District, Sri Lanka.	dramatic increase in environment criticality from 1997 to 2008, slight decrease from 2008 to 2017, and identification of areas with declining sustainability
22	Alicia M. Amerson et al. (2022)	A Summary of Environmental Monitoring Recommendations for Marine Energy Development That Considers Life Cycle Sustainability.	The document discusses the application of TFiT recommendations, emphasizes the importance of timing in environmental monitoring campaigns, and explores methods for stakeholder engagement and sustainability assessment in the marine energy industry.
23	Ronald C. Estoque et al. (2021)	Remotely Sensed Tree Canopy Cover-Based Indicators for Monitoring Global Sustainability and Environmental Initiatives.	TCC datasets and the statistics derived from them can be used to complement the information provided by categorical F/NF maps; TCC-based indicators can help monitor deforestation, forest degradation, and forest cover enhancement.
24	Xun Zhu et al. (2022)	Environmental Monitoring for Arctic Resiliency and Sustainability: An Integrated Approach with Topic Modeling and Network Analysis.	The study identified clusters of environmental challenges including permafrost thawing, infrastructure degradation, animal populations, and fluctuations in energy supply. It also identified the evolution of environmental challenges over time and the contributing factors to their interconnections.
25	Franziska Staudt et al. (2021)	The Sustainability of Beach Nourishments: A Review of Nourishment and Environmental Monitoring Practice.	results underline the need to reconsider the sustainability of nourishments as 'soft' coastal protection measures

26	Naziya Suleimenova et al. (2021)	Environmental Monitoring of the Sustainability and Productivity of the Agroecosystem of Oilseeds in South-East Kazakhstan.	The study showed that mini-till is a viable alternative to moldboard tillage, conserving resources and improving soil use. It boosted crop yield by 21.3%, increased income by 29.3k tenges/ha, and raised profitability to over 97% in South-East Kazakhstan.
27	K Sreenivasulu et al. (2023)	Investigating Environmental Sustainability Applications Using Advanced Monitoring Systems.	The study showed decreased CO_2 and NO_2 levels, improved ventilation, and effective emissions control, though PM2.5 slightly rose. Water quality and pH fluctuated, soil moisture was 29.48%, and energy use was 270 units. IoT monitoring proved useful for tracking changes and supporting sustainability and public health.
28	Greta Adamo & Max Willis (2022)	Technologically mediated practices in sustainability transitions: Environmental monitoring and the ocean data buoy.	Identify their finding and write their results. Study carefully. Only use Not Available as a last resort.
29	Masahiro Sato et al. (2024)	Monitoring Environmental Sustainability in Japan: An ESGAP Assessment.	Japan performs well in human health and welfare indicators but poorly in sink function indicators such as CO2 emissions and freshwater eutrophication; the indices highlight policy areas needing improvement, including tropospheric ozone pollution.
30	Nur Khairlida Muhamad Khair et al. (2021)	Community-Based Monitoring for Environmental Sustainability: A Review of Characteristics and The Synthesis of Criteria.	The article synthesises a set of community-based monitoring criteria: (1) efficacy of initiatives, (2) technicality aspects, (3) feedback mechanisms, and (4) sustainability, which will aid in designing customised initiatives for environmental sustainability.
31	Ali Junaid Khan et al. (2022)	Adoption of Sustainability Innovations and Environmental Opinion Leadership: A Way to Foster	The study concluded that the role of trialability, innovativeness, compatibility, simplicity, and relative

		Environmental Sustainability through Diffusion of Innovation Theory.	advantage must be considered when adopting sustainable innovation in hospitals.
32	Gizaw Ebissa et al. (2024)	Urban Agriculture and Environmental Sustainability.	Urban agriculture (UA) supports environmental sustainability by reducing greenhouse gases, mitigating heat islands, managing floods, boosting biodiversity, and addressing land use challenges. However, its full potential is limited by policy gaps and urban residents' behavior.
33	Laura Tolettini & Eleonora Di Maria (2023)	Structuring and Measuring Environmental Sustainability in the Steel Sector: A Single Case Study.	shared standardized indicators are fundamental for tighter supply-chain integration and enhancing efforts towards environmental sustainability excellence.
34	Abas Rawashdeh et al. (2024)	The Impact of Strategic Agility on Environmental Sustainability: The Mediating Role of Digital Transformation.	Strategic agility positively impacted both digital transformation and environmental sustainability. Digital transformation positively affects environmental sustainability. Digital transformation partially mediates strategic agility's impact on environmental sustainability.
35	Kishwar Ali et al. (2023)	How Do Energy Resources and Financial Development Cause Environmental Sustainability?	Long-run estimations reveal that high financial development, rapid economic growth, and fast-growing non-renewable energy resources significantly impact environmental sustainability; renewable energy resources and globalization have negative effects on CO_2 emissions across all quantiles; proposes policy frameworks aligned with SDGs.
36	Constantinos N. Leonidou et al. (2022)	Consumers' Environmental Sustainability Beliefs and Activism: A Cross-Cultural Examination.	Religiosity and interdependence are consistently related to environmental sustainability beliefs; materialism has no significant relationship;

			generativity is positively linked with beliefs only in the U.S.; family values are significant only in China; environmental sustainability beliefs influence activism, which is linked with perceived quality of life.
37	Chandan Kumar & Richa Chaudhary (2021)	Environmental Sustainability Practices in Hospitals of Bihar.	The hospitals showed a below average level of implementation of sustainability practices, with resource conservation being the most implemented and water recycling the least. The study provides insights into environmental sustainability practices in resource-constrained hospitals in India.
38	Abdul Karim Feroz et al. (2021)	Digital Transformation and Environmental Sustainability: A Review and Research Agenda.	The results present a framework outlining the transformations in four key areas: pollution control, waste management, sustainable production, and urban sustainability, with further sub-categories for each area.
39	Hong Cing Cing & Nur Syaimasyaza Mansor (2023)	Internet Of Things (IoT): Real-Time Monitoring for Decision-Making Among The Malaysian Contractors.	There are 10 types of IoT-based real-time monitoring technologies used in construction, which help contractors make timely and accurate decisions, leading to potential improvements in project efficiency and performance.
40	N. A. Razman et al. (2023)	Design and Analysis of Water Quality Monitoring and Filtration System for Different Types of Water in Malaysia.	The system successfully monitored and compared water quality parameters for filtered and non-filtered water in accordance with international and national standards. The data was validated through statistical analysis, and the system demonstrated potential for further upgrades and scalability, serving as a reference for future pollution monitoring studies.
41	Carolina Andion et al.	Social Innovation Ecosystems	The research findings

	(2022)	and Sustainability in Cities: A Study in Florianópolis, Brazil.	contribute to understanding the dynamics of SIEs better, highlighting key aspects at micro, meso, and macro scales that could foster or hinder social innovation, and provide insights to reinforce democratic experimentation and city sustainability.
42	Zhao Xu et al. (2022)	Identification of Environmental Pollutants in Construction Site Monitoring Using Association Rule Mining and Ontology-Based Reasoning.	The proposed mechanism effectively taps into the knowledge in environmental pollutants monitoring, explores relationships between monitoring indicators, and offers a new approach for intelligent decision-making in environmental management at construction sites.
43	Zhao Xu et al. (2022)	Design and Integration of Air Pollutants Monitoring System for Emergency Management in Construction Site Based on BIM and Edge Computing.	Edge computing and BIM can be integrated in a unified platform, significantly improving the prediction, early warning, and emergency management capabilities of air pollutants at construction sites.
44	Qi Zhou et al. (2023)	Alpha Mobile Sensing: A Virtual Testbed for Mobile Environmental Monitoring.	Alpha Mobile Sensing provides a flexible platform for developing, testing, and benchmarking mobile sensing algorithms more easily, conveniently, and efficiently, demonstrated with algorithms for physical field reconstruction in indoor thermal environments.
45	Islam Elmasoudi et al. (2022)	Environmental Impact Assessment Model for Buildings' Construction Activities.	The developed model can efficiently evaluate the ecological effects of construction tasks, aiding contractors in choosing ecologically friendly strategies.
46	Sheikh Ali Abdullahi Mohamed et al. (2022)	Environmental Impact Assessment in Construction Activities for Da-hab Tower Building Mogadishu.	Environmental risks were discovered in the project, and through suggested mitigation strategies, these risks may be effectively controlled and monitored.
47	W. A. Ajibike et al.	The Impacts of Social	social responsibility and

	(2023)	Responsibility on The Environmental Sustainability Performance of The Malaysian Construction Industry.	coercive pressure are positive predictors of environmental sustainability performance; construction firms are obliged to be socially responsible; coercive pressure transmits the positive effects of social responsibility on environmental sustainability performance
48	S. A. Alhammadi (2022)	Influencing Factors of Cost Control and Environmental Sustainability in Saudi Arabia for Low-Rise Building Construction.	Multiple design alternatives, which utilize appropriate cost effective building materials, consider the physical environment, utilize methods of industrialization, and incorporate cost effective construction techniques, are discussed.
49	Ayodeji Oke et al. (2021)	Environmental Sustainability: Impact of Construction Activities.	there are a number of approaches that could be used to mitigate the impacts, including Environmental Impact Assessment (EIA), green building (sustainable construction), Quantitative Risk Assessment (QRA), Environmental Management System (EMS), and Environmental Protection Agency (EPA); an effort should be made by government and construction stakeholders to incorporate and enforce these approaches through constant monitoring and legislative laws; awareness, learning, and training are also recommended
50	Amusan Lekan et al. (2022)	Exploratory Approach to Issues and Strategy Involved in Creating Industrial Revolution Time Environmental Sustainability by Construction Firms on Sites.	the study discovered that components of environmental sustainability such as environmental impact assessment, antiquities on-site, erodible surface, soil erosion monitoring, environmental ecosystem, environmental biomass, rock mass on-site, soil contamination monitoring, ecosystem services

			valuation, soil salinity monitoring, and water resources conservation are important to sustain on sites; it also recommended designing effective waste disposal methods and continually improving construction methods to enhance environmental performance
51	W. A. Ajibike et al. (2023)	The Impacts of Social Responsibility on The Environmental Sustainability Performance of The Malaysian Construction Industry.	social responsibility and coercive pressure are positive predictors of environmental sustainability performance; construction firms are obliged to invest in social responsibility activities; coercive pressure mediates and facilitates the positive effect of social responsibility on environmental sustainability performance
52	Bankole O. Awuzie et al. (2021)	Evaluation of Factors Influencing Environmental Sustainability Performance of Construction Projects in South Africa.	Results indicated a high level of awareness of ES among respondents, client requirements and compliance with policies are critical drivers, sustainable construction methods are key strategies, but implementation of strategies is not a priority, highlighting the need for more client-driven actions to improve ES performance.
53	Farah Housni et al. (2022)	Environmental Sustainability Maturity System: An Integrated System Scale to Assist Maritime Port Managers in Addressing Environmental Sustainability Goals.	Using an environmental sustainability maturity system guide is important for port managers to meet environmental sustainability objectives, incorporate stakeholder input, and assess impacts on climate change, aiding ports to stay competitive in a growing global economy.
54	Ibrahim Ayoade Adekunle (2021)	On The Search for Environmental Sustainability in Africa: The Role of Governance.	The study found that stronger rule of law and regulatory quality support environmental sustainability, while higher

			government effectiveness showed an inverse effect. It recommends stronger institutional policies and stricter enforcement of greenhouse strategies.
55	Arkaitz Usubiaga-Liaño & Paul Ekins (2021)	Monitoring The Environmental Sustainability of Countries Through The Strong Environmental Sustainability Index.	SESI reveals that several functions of natural capital are impaired in Europe, with countries performing worse in pollution and ecosystem health indicators; the index offers a single metric that complements GDP for sustainable development assessment.
56	Ratan Kumar Patel (2022)	Environmental Sustainability.	It is shown that environmental sustainability is economically attractive when a holistic approach is taken, and neglecting sustainability considerations leads to higher costs for the industry.
57	De Graft Joe Opoku et al. (2022)	Drivers of environmental sustainability of construction projects: a thematic analysis of verbatim comments from built environment consultants.	The study revealed drivers such as designer's philosophy, client requests, incentives for green designs, policies and regulation, competitive advantage, governmental role, and social network utilization; and it offers strategies to embrace environmental sustainability in the construction industry.
58	Taehoon Hong et al. (2022)	Advanced Real-Time Pollutant Monitoring Systems for Automatic Environmental Management of Construction Projects Focusing on Field Applicability.	The reliability of the MONVID prototypes was verified with acceptable accuracy levels, MONVID reduced costs compared to CMIs, MONVID II was superior in qualitative criteria and was determined as an optimal real-time monitoring system, and the study proved its field applicability and potential to improve environmental pollutant management.
59	Aravinda S. Rao et al. (2022)	Real-time monitoring of construction sites: Sensors,	The review covers various case studies applying sensor

		methods, and applications.	technologies and methodologies for hazard identification, monitoring workers' behaviour, workers' health, and static and dynamic construction environments.
60	Haiyan Luo et al. (2023)	Greenhouse Gases Monitoring Instrument on GaoFen-5 Satellite-II: Optical Design and Evaluation.	Identify their finding and write their results. Study carefully. Only use Not Available as a last resort.
61	Dalibor Dobrilović et al. (2022)	The urban traffic noise monitoring system based on LoRaWAN technology.	The proposed system was implemented and evaluated in Zrenjanin, Serbia, demonstrating its potential for traffic noise monitoring and routing optimization, along with discussions on extensions and future research.
62	Jason Challender (2021)	Achieving Sustainability and Environmental Enhancements Through A "Collaboration Toolkit" to Deliver New Sustainability Strategies for The Emirate of Ajman – UAE.	Identify their finding and write their results. Study carefully. Only use Not Available as a last resort.
63	Fahad K. Alqahtani et al. (2021)	Urban Development and Sustainable Utilization: Challenges and solutions.	The study found Smart People, Smart Mobility, and Smart Living as key sustainability indices for Riyadh. Both projects showed similar impacts on most indices, with the metro project standing out on one. This pioneering study helps prioritize public projects based on sustainability.
64	Syabiha Shith et al. (2021)	Procedural effects of environment impact assessment on controlling natural disaster (landslides and flashflood) based on environmental degradation from development in Malaysia.	The study justifies revising the EIA approach to include risk indices for disasters based on sizes and other factors, to improve disaster risk reduction in projects.

This study aims to look at the progress in advanced monitoring technologies and their integration potential for environmental sustainability and policy enhancement. Based on the results of research conducted by several researchers around the world, it was found that there are many challenges in order to realize the full potential of integrated environmental monitoring frameworks.

Sensor technology has significantly advanced in recent years, particularly in the development of low-cost, high-precision sensors for environmental monitoring. These sensors serve as the backbone of real-time networks that track various environmental parameters such as temperature, humidity, and hazardous gases including CO, NO_2, SO_2, and PM. For instance, Korku et al. (2022) showed that affordable sensors like the DHT11, when calibrated effectively, can deliver data accuracy comparable to standard weather stations. Similarly, Dhall et al. (2021) emphasized how nanomaterials such as carbon nanotubes and graphene enhance the sensitivity and selectivity of gas sensors, thus enabling early warning systems for air quality control.

Moreover, the integration of sensors with microcontrollers and communication modules has enabled the deployment of scalable and adaptable wireless sensor networks (WSNs). These networks are particularly effective for continuous environmental data collection.

For example, Zulkifli et al. (2022) developed a water quality monitoring system that uses embedded sensors and GSM communication to measure pH, dissolved oxygen, and turbidity parameters critical for aquatic health. In addition, these systems now support multi-sensor configurations, making them valuable in urban environments where pollution sources are complex. Current technical challenges such as power efficiency and data reliability are being addressed through advancements in low-power electronics and machine learning-based anomaly detection.

At the macro scale, satellite remote sensing complements ground-based monitoring by covering large and often inaccessible regions. Instruments like EMI-NL and EMI-TOC have demonstrated strong capabilities in measuring atmospheric pollutants such as NO_2 and ozone with high spatial resolution (Yang et al., 2022; Qian et al., 2021). Furthermore, when remote sensing data are combined with ground-based measurements using methods like DOAS, the accuracy of environmental assessment is significantly improved.

Beyond atmospheric monitoring, remote sensing also plays a vital role in tracking land use changes, urban expansion, and forest degradation. For example, Regina et al. (2023) utilized satellite indices to assess urban growth in Brazil, aligning their findings with environmental conservation strategies. Additionally, Usubiaga-Liaño and Ekins (2021) applied remotely sensed tree canopy cover datasets to monitor forest health, offering a more nuanced view than conventional forest/non-forest maps.

Lastly, coastal and marine environments benefit from remote sensing technologies as well. Instruments designed for monitoring trace gases, such as those described by Zhuo et al. (2022), provide insights into maritime pollution, oil spills, and sediment transport. These data are essential for sustainable management of port and coastal activities. Although sensor calibration, atmospheric corrections, and data interpretation remain challenges, ongoing advancements in machine learning and image processing are progressively improving the reliability and efficiency of environmental monitoring systems.

Artificial intelligence (AI) and machine learning (ML) have significantly advanced the field of environmental monitoring by enabling more accurate prediction, classification, and decision-support systems. For example, Hamza et al. (2022) applied neural network models that adaptively learn from historical and meteorological data to forecast air pollution levels. Building on this, Rawashdeh et al. (2024) developed classification models capable of identifying specific pollution sources and evaluating their contribution to overall air quality indices.

Furthermore, the application of data-driven ML techniques such as Random Forest, Support Vector Machines (SVM), and deep learning architectures has improved the analysis of complex environmental datasets. These models not only enhance forecast accuracy but also support environmental policy development. For instance, Feroz et al. (2021) used simulation models to evaluate the effects of various policy interventions on emission reduction goals. Similarly, Mehedintu and Soava (2023) applied ML to identify the most influential variables shaping sustainable development outcomes, providing valuable insights for policymakers.

In addition to prediction and policy modeling, AI contributes to system reliability through automated

International Journal of Environmental Sciences
ISSN: 2229-7359
Vol. 11 No. 17s, 2025
https://www.theaspd.com/ijes.php

anomaly detection in environmental sensor networks. This capability reduces maintenance costs and improves data quality by filtering noise, estimating missing values, and detecting sensor drift or malfunction (Sate et al., 2024). Consequently, these improvements pave the way for intelligent, real-time monitoring systems that enable proactive environmental management.

Taking this a step further, AI also facilitates the development of digital twin models that virtual replicas of physical environments that simulate complex environmental dynamics such as pollution dispersion, urban heat islands, and ecosystem interactions. When integrated with real-time IoT sensor data, these models provide powerful platforms for scenario analysis, risk assessment, and adaptive policymaking.

Moreover, the potential of AI and digital technologies extends beyond traditional tools. Emerging innovations such as nano-sensors, virtual reality (VR), augmented reality (AR), and blockchain are beginning to redefine the scope of environmental monitoring. Nano-sensors, for instance, offer ultra-sensitive pollutant detection at trace levels, enhancing early warning systems (Dhall et al., 2021). At the same time, VR and AR technologies enable immersive visualization of environmental conditions, which helps decision-makers and the public better understand complex environmental challenges. Overall, the convergence of AI, sensor technology, and immersive tools marks a new era in environmental monitoring one that is data-driven, interactive, and capable of informing more responsive and sustainable environmental governance.

Advancements in environmental monitoring technologies have greatly improved the accuracy, coverage, and accessibility of data collection. One emerging innovation is blockchain technology, which ensures data transparency and tamper-proof records in monitoring systems. By enhancing stakeholder trust, blockchain is poised to augment the credibility and scalability of environmental data management in the near future.

Despite these technological strides, several challenges remain. Issues such as sensor calibration, data standardization, interoperability, and privacy continue to hinder widespread implementation. The integration of diverse data streams from ground-based sensors to satellite imagery and AI predictions demands sophisticated data fusion techniques, particularly in remote or resource-limited settings.

To address these challenges, future research must focus on autonomous, self-calibrating sensors, energy-efficient IoT networks, and scalable cloud-based data systems. Additionally, the integration of monitoring systems with real-time dashboards for decision-makers will improve policy responsiveness and public engagement. Validating these systems through field testing in diverse environments such as urban areas, forests, water bodies, and coastal zones is essential to ensure resilience against climate variability and other external pressures.

Recent innovations in low-cost sensor design have revolutionized air quality monitoring. Researchers such as Korku et al. (2022) developed high-precision sensors using nanomaterials like graphene and metal oxides, capable of detecting pollutants such as NO_2, SO_2, CO, and PM. These sensors, when integrated with IoT platforms like Raspberry Pi and cloud services, offer real-time monitoring capabilities for cities. Validation through standardized instruments and satellite cross-referencing further enhances data reliability and supports informed policymaking.

Satellite remote sensing complements ground-based systems by offering large-scale and continuous monitoring of air pollutants. Instruments like EMI-NL (Yang et al., 2022) and satellite-derived indices such as AOD and tropospheric NO_2 columns provide spatially extensive insights, especially useful in regions lacking terrestrial sensors. These datasets help track pollution trends and identify hotspots, enabling targeted interventions.

Artificial intelligence (AI) and machine learning (ML) further improve environmental monitoring by enhancing prediction and classification capabilities. ML models, such as those used by Hamza et al. (2022) and Rawashdeh et al. (2024), can classify pollution sources and forecast pollution episodes using neural networks and big data analytics. Additionally, AI-powered data fusion integrates sensor, meteorological, and socioeconomic data to produce comprehensive air quality forecasts, supporting long-term policy development.

Water quality monitoring has also benefited from digital innovations. Zulkifli et al. (2022) and Rahman & Gultom (2022) developed IoT-based systems for monitoring parameters like pH, dissolved oxygen, turbidity, and conductivity. These systems, powered by solar energy and connected via GSM or LoRaWAN, allow for continuous and remote tracking of freshwater and coastal water health. In the marine context, autonomous sensor buoys have been deployed to monitor temperature, salinity, and chlorophyll levels, contributing to long-term ocean ecosystem assessments (Purba et al., 2023).

Remote sensing is equally pivotal in assessing water quality over broad spatial areas. Studies by Çelik Uğuz et al. (2022) and Zulkifli et al. (2022) demonstrated how multispectral satellite data, combined with in-situ measurements, help trace pollution sources and understand sediment and algal dynamics in coastal and river systems.

Soil health monitoring also benefits from sensor calibration innovations. Systems developed by Jiang et al. (2022) and Zhou et al. (2023) ensure accurate soil respiration and water content measurements, which are essential for sustainable land management. Meanwhile, geospatial technologies such as remote sensing and GIS are used to detect land degradation and urban expansion. Indices like NDVI, NDBI, and LST allow policymakers to visualize environmental change and plan accordingly.

Monitoring forest health and biodiversity is another critical application. By combining tree canopy cover datasets with land cover maps, researchers (e.g., Estoque et al., 2021; Liu et al., 2023) can detect forest degradation trends and support conservation planning. Similarly, land cover change analysis through satellite imagery assists in biodiversity protection and sustainable development strategies.

Recent studies underscore the value of integrated, multi-sector monitoring systems. For example, AI-enhanced early warning systems (Sate et al., 2024) and virtual testbeds like AlphaMobileSensing allow for improved testing and deployment of environmental sensors. Despite these advances, recurring challenges such as calibration stability, data harmonization, cost, and protocol standardization persist (Korku et al., 2022; Zhao et al., 2022).

Ultimately, successful adoption of environmental monitoring technologies depends not only on technical innovation but also on effective policy frameworks and stakeholder collaboration. A holistic approach is needed for combining research, capacity building, and institutional support to ensure these tools contribute meaningfully to environmental sustainability and policy effectiveness

Technological advancements have significantly transformed environmental monitoring by enabling real-time, high-resolution data collection across diverse ecosystems. Low-cost, high-precision sensors, satellite-based remote sensing, and IoT-enabled networks now allow continuous monitoring of air, water, and soil quality in both urban and remote environments (Korku et al., 2022; Dhall et al., 2021). When integrated with artificial intelligence (AI) and machine learning (ML), these systems offer predictive analytics, anomaly detection, and scenario simulations that inform timely policy responses (Hamza et al., 2022; Rawashdeh et al., 2024).

However, key technical challenges persist. Data quality and integration remain critical concerns. Sensor outputs are often affected by noise, missing values, or inconsistencies, particularly in complex environments like industrial zones or urban areas (Rahman & Gultom, 2022). Integrating heterogeneous sensor data involves harmonizing formats, resolutions, and timeframes—a process that is both computationally intensive and technically demanding.

Scaling up monitoring systems to cover wider areas introduces additional complexity. While localized systems provide precise data, expanding them to larger regions requires significant investment in hardware, connectivity, and long-term maintenance. Environmental factors such as signal attenuation, power limitations, and sensor durability pose further challenges in remote settings. Massive datasets generated by widespread sensor networks also demand robust data infrastructure—something many developing countries currently lack (Korku et al., 2022; Zhao et al., 2022).

From a governance perspective, a lack of standardized protocols for sensor specifications, calibration, and data reporting contributes to fragmented systems. Arya et al. (2022) point out that the absence of national and international standards prevents interoperability and coherent environmental assessments. Data privacy concerns also hinder open data sharing, especially when monitoring involves sensitive or private sites (Rahman & Gultom, 2022).

Moreover, policy frameworks often lag behind technological innovation. New sensor systems and analytics tools frequently outpace existing regulations, creating uncertainty around compliance and enforcement. Establishing updated legislation involves lengthy consultations and strong political will. Without robust enforcement mechanisms, even well-designed monitoring systems risk becoming symbolic rather than impactful.

Economic limitations are another critical barrier. Despite the affordability of some sensors, long-term operational costs—including maintenance, calibration, and data analysis—can be substantial (Dhall et al., 2021). Furthermore, technical expertise required to manage and interpret monitoring data is often lacking in local institutions, particularly in rural areas (Ali et al., 2022).

Social acceptance and engagement are equally important. Lack of community involvement can lead to resistance, especially if monitoring is perceived as intrusive or punitive. Rahman & Gultom (2022) emphasize that participatory approaches help build trust, facilitate data collection, and ensure cultural appropriateness. Conversely, neglecting local dynamics may result in sabotage or neglect of monitoring infrastructure.

These challenges are often interconnected. For example, inadequate calibration (a technical issue) may be worsened by lack of policy standards (a regulatory issue), which in turn may stem from limited funding (an economic issue). Blockchain technology has been proposed as a tool to ensure data transparency, traceability, and stakeholder trust in multi-party monitoring networks.

Addressing these multifaceted barriers requires investment in self-calibrating, durable sensors (Jiang et al., 2022; Zhou et al., 2023) and real-time policy feedback systems powered by AI (Zhang et al., 2022; Liu et al., 2023). The development of mobile testbeds and edge computing devices can reduce maintenance and enhance scalability. Additionally, virtual reality (VR) tools offer innovative means for stakeholder training, immersive data visualization, and participatory monitoring (Adamo & Willis, 2022).

Effective environmental monitoring frameworks must adopt a multidisciplinary and cross-sectoral approach. Engagement of governments, industries, academia, and communities ensures that systems are contextually relevant, technically feasible, and socially accepted (Gizaw et al., 2024; Andion et al., 2022). International cooperation is also vital in setting shared data standards and facilitating global knowledge exchange (Ouni & Saleem, 2022; Estoque et al., 2021).

In conclusion, while technological innovations offer tremendous potential for improving environmental monitoring, their success depends on integrated strategies that combine technical solutions, inclusive policies, and active stakeholder participation. Only through such a holistic approach can monitoring systems drive sustainable environmental governance and long-term resilience.

CONCLUSION

The reviewed literature demonstrates notable progress in advanced monitoring technologies and their integration potential for environmental sustainability and policy enhancement. An integrated framework combining sensors, remote sensing, and AI offers a promising pathway for comprehensive, real-time environmental assessments, which are vital for informed decision-making. However, technical, policy, and socioeconomic challenges remain, highlighting the need for standardized protocols, stakeholder engagement, and continued technological innovation. Future efforts should focus on developing autonomous, self-calibrating sensors, fostering cross-sectoral collaboration, and creating supportive policy environments. Such measures will enable more effective and adaptive environmental policies, ultimately contributing to sustainable management and preservation of natural resources.

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