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REVIEW

Internet-of-Things-blockchain integration in environmental pollution monitoring data management: trends and techniques

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Abstract

The increasing industrialization and urbanization have amplified pollution, leading to the release of contaminants harmful to ecosystems and human health. Using the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) methodology. This review explored the integration of Internet-of-Things and blockchain technologies in environmental pollution monitoring and data management by examining 108 articles. The study highlighted the drawbacks of traditional monitoring methods, including high costs, time consumption, and limited scalability, prompting the adoption of Internet-of-Things-based solutions. In addition, by integrating blockchain technology, the frameworks ensure data authenticity, transparency, and traceability. A comparative analysis of existing Internet-of-Things-blockchain models shows that, while they improve real-time data monitoring and offer enhanced security, challenges such as high computational complexity and inadequate sensor coverage persist. The identified key issues include the need for more scalable, low-cost sensor systems and lightweight frameworks to handle diverse environmental data; the importance of selecting appropriate blockchain networks and consensus algorithms to balance security, scalability, and efficiency; and addressing lax-cryptic trustworthiness in the process, amongst other issues. Future directions solicit the convergence of Artificial Intelligence, Internet-of-Things, and blockchain technologies for more efficient and cost-effective pollution monitoring, to ensure real-time data security, authenticity, and environmental sustainability.

Keywords Blockchain framework · Contamination · Control · Data storage · Environs · Tracking

Introduction

Environmental toxicology is an important discipline at the forefront of addressing the intricate connection between human activities, health, and the environment, which is currently facing unprecedented challenges due to escalating environmental pollution. Significant levels of industrialization and urbanization have occurred throughout the world in recent decades, resulting in the discharge of several toxins into the environment (Parida et al. 2021). These pollutants, referred to as contaminants of emerging concern (CECs) or emerging pollutants (EPs), remain largely unregulated under existing environmental legislation, having a high potential for damage. They include hazardous heavy metals, microplastics, cosmetics, agrochemicals like pesticides and fertilizers, medications, industrial wastes, and petroleum hydrocarbons (Haruna et al. 2020; Rathi et al. 2021). Biodiversity, ecosystem function, and public health are significantly impacted by the expanding list of pollutants that are being released into the environment by various sectors, causing diseases such as cancer, immune system dysfunction, respiratory system damage, and neurological problems in humans (Gatti et al. 2023). As a result, there is increasing concern for real-time effective environmental pollution detection, monitoring, and data management.

Pollutants of various origins, even in low concentrations, are often present in the environment and can infiltrate the human body through different pathways, such as ingestion, skin absorption, and inhalation, potentially leading to various diseases as reported by Zhang et al. (2021); Teengam et al. (2021). Environmental pollution monitoring involves

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tracking, identifying, and measuring the levels of pollutants in the environment, as highlighted in Fig. 1. Considering the present developments and industrial activities, accurate and timely alerts enabled by real-time monitoring and data collection will provide informed and technical aid for environmental public administration and oversight and allow government agencies, individuals, com-panies, and other stakeholders to observe and react to changing conditions both on-site and in-doors (Zhong et al. 2022; He et al. 2023). For a sustainable green environment via effective contamination remediation and compliance with regula- tions and standards, environmental data quality, storage, and traceability cannot be overemphasized.

Distinctive conventional laboratory methods for detecting pollutants, such as spectrofluorimetry Attia et al. 2023), atomic absorption spectroscopy, gas chromatography/mass spectrometry (Y. ZHang et al. 2023), High-performance liquid chromatography (HPLC) (Wo´zniak et al. 2023), and enzyme -linked immunosorbent assay (ELISA) have been designed and widely adopted by researchers in the field. Although the aforementioned techniques are highly reliable and accurate, there are notable drawbacks such as high cost, time-consuming, high operational skill, and non-scalability due to a lack of on-site detection (Olabintan et al. 2024). To resolve the limitations of traditional monitoring systems, the use of sensors, and nanozyme- based point-of-care testing (POCT) devices in detecting pollutants in different samples was explored (Wang et al. 2024; Gallego et al. 2023). Additionally, numerous Internet of Things (IoT) systems equipped with diverse monitoring devices and sensors have been developed to evaluate pollutant levels. For example, Asha et al. (2022) introduced a novel ETAPM-AIT method for predicting air quality by utilizing IoT-based sensors in combination with machine learning (ML) techniques. A directed acyclic graph (DAG)-structured wireless sensor network (WSN) was employed by Lin et al. (2020) for real-time tracing of water pollution sources. Many more cutting-edge sensor technologies have been applied. These suggested systems, however, have certain limitations.

Despite advancements, many nations and areas continue to lack adequate envi- ronmental monitoring, which prevents huge populations from having access to the data needed to manage pollution and make wise health decisions (Fu et al. 2023). This disadvantage stems from the insufficient gathering of thorough contamination data from both indoor and outdoor locations. It cannot thoroughly investigate the data's veracity and validity in a short period (Jianfeng Li et al. 2021a, b; ZHang and Dong 2021). Additionally, to protect business interests, there is environ- mental data fraud/falsification by some stakeholders,

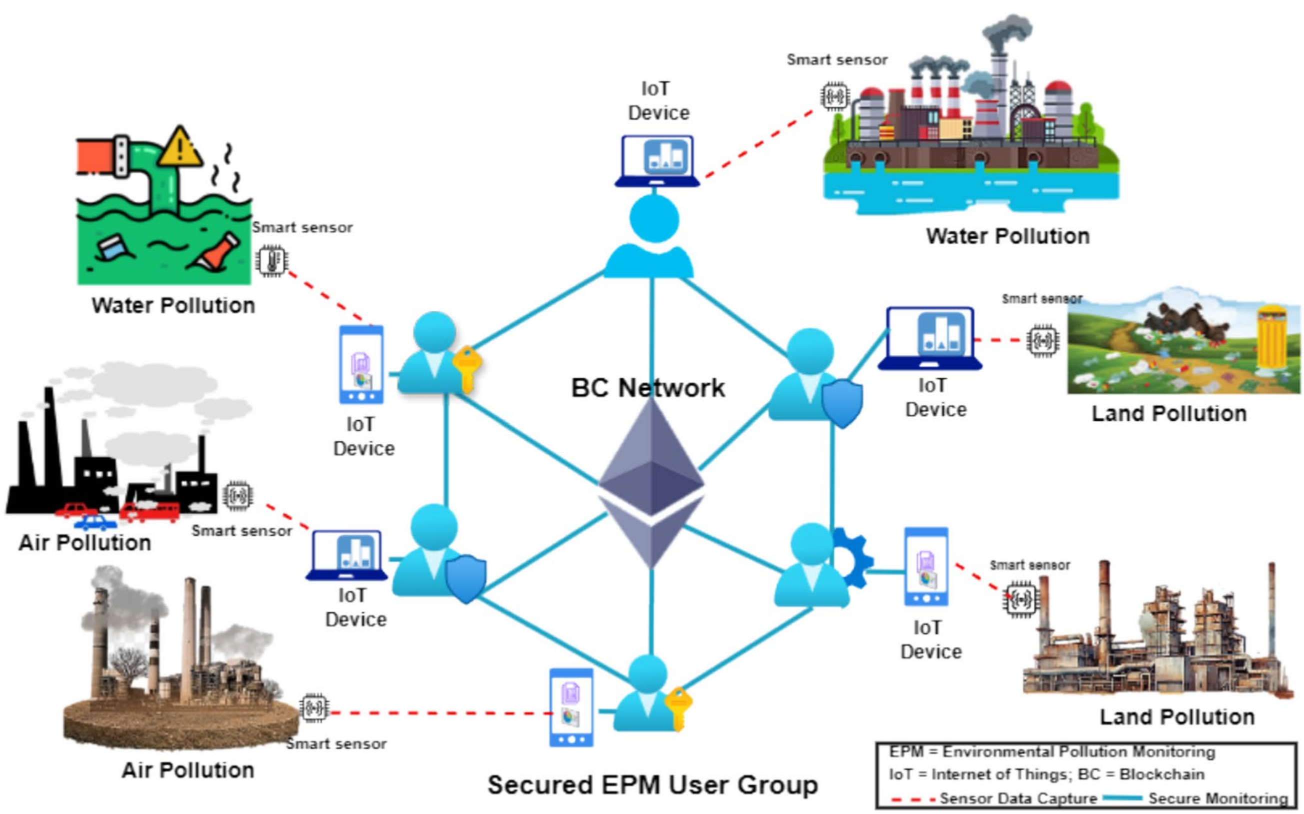


Fig. 1 Smart environmental pollution monitoring systems using IoT and sensors

therefore, environmental data originality, transparency, and traceability are questionable (Zhong et al. 2022; Xingbo et al. 2024). Previously conducted studies have primarily concentrated on presenting several techniques of measurement (e.g., installation location, categories of sensors, and intervals of measurement) for gathering data in real-time, primarily on air and water bodies. Furthermore, there is limited discussion on ensuring the security and reliability of the data. The actual volume of pollutants, along with the associated pollution management processes and monitoring, is not sufficiently documented or tracked. Therefore, there is a need for an automated blockchain-based pollution monitoring system—a secure and transparent system for recording information, with dependable data storage and retrieval capabilities.

Overview of literature review

Several reviews and surveys have made consistent efforts to peruse the technological development and gaps in environmental monitoring, as shown in Table 1. First, the works of (Pant et al. 2019; Idrees and ZHeng 2020) are linked to the use of low-cost wireless sensors and IoT in environmental domains, paving the way for real-time EPM data generation and collection. Also, the integration of IoT-AI data computing in real-time tracking of environmental conditions was examined by Kaginalkar et al. 2021; Popescu et al. 2024. These works laid the foundation for cognitive inferencing and spatio-temporal analysis of EPM data needed for informed decision-making.

Lastly, with the increasing and promising benefits of blockchain application for monitoring and reducing environmental impact, the works of Jin and Chang (2023); Rani et al., (2024) examined the importance of BC to improving supply chain in environmental management. However, none of these works adopted a systematic approach in reporting their findings. Furthermore, unlike this review, none of the previous studies comprehensively examined the impact of low-cost sensor-based IoT-BC strategies on environmental pollution monitoring and data management, nor examined the integration of blockchain technology in EPM. Therefore, considering the decentralization, cryptographic algorithm, and smart contract intelligent nature that blockchain provides for real-time secured data transmission, this study not only addresses the gaps in previous works but also provides a platform for efficient and authentic EPM data security. It also explores the current trends in IoT-BC-based technologies in environmental pollution detection, monitoring, and data management.

The specific contributions of this paper are;

1. Examined empirical and didactic evaluations of contemporary threats arising from misappropriated EPM data.
2. Explored the dynamics and drawbacks in contaminants detection techniques; from conventional to convergence-based approaches.
3. Investigated the diverse IoT-BC frameworks for secured EPM data management and use cases of hybrid-based technologies.
4. Highlighted open research issues and provided future directions for implementing hybrid IoT-BC techniques for green environment sustainability.

In this review, Sect. "Overview of literature review" summarizes the adopted review methodology. Section 3 presents a detailed analysis of trends in global environmental pollution. Sect. "Articles selection and exclusion criteria" discusses the evolution of contaminant detection techniques. Sect. "Article search result" delves into the various IoT-BC approaches for secure EPM. Sect. "Research type" highlights open research issues and future directions, Sect. 7 concludes the paper. Table 2 highlights the list of terms commonly used.

Materials and methods

This research employs the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) review methodology (Ajakwe et al. 2022). A thorough search was conducted on seven databases: IEEE Xplore, MDPI, Taylor & Francis, SpringerLink, Elsevier, PubMed library, etc., as shown in Table 3. The search was performed on each database using key-words “environmental monitoring” and “blockchain” or “IoT-blockchain framework” and “contaminant data”, or “environmental data storage” and “integrated technolo- gies”. The keywords were chosen to align with the PICOS strategy (participants, interventions, comparators, outcomes, and study design/limitations) to enable a com- prehensive search and ensure sufficient coverage of the study’s scope. Articles published between 2019 and 2024 were considered.

Articles selection and exclusion criteria

The authors conducted an initial screening of all retrieved articles. After reviewing the titles and abstracts, any articles with duplicate titles or content were eliminated. The authors then assessed the article’s overall content and verified its eligibility. Articles were considered eligible for the review based on the following inclusion criteria:

- That the paper appears in conference proceedings or a respected journal.

Table 1 Comparative analysis of related studies on IoT-blockchain frameworks in environmental pollution monitoring & data management

Sn	Year	References	Paper type	Target area & scope	Findings	BCM
1	2019	Pant et al. (2019	Survey	Monitoring particulate matter using sensors-IoT in monitoring stations	Generation of high-resolution data at a lower cost	No
2	2019	Arora et al. (2019)	Survey	IoT-based models across different environmental monitoring domains	Wireless communication tech- nologies enabling real-time updates, need for the scalabil- ity of sensor networks and data transmission reliability. Systems face challenges such as sensor calibration, network scal- ability, and data accuracy	No
3	2020	Idrees and Zheng (2020)	Review	Low-cost ambient IoT-Wireless Sensor Networks (WSN) in both indoor and outdoor environments		No
4	2021	Kaginalkar et al. (2021)	Review	IoT-AI big data comput- ing for air quality man- agement (AQM) within smart city	Real-time pollution monitoring, emission assessment, prediction, and control strategies	No
5	2021	Ahmad et al. (2021)	Survey	Real-time tracking of waste, implementation of blockchain-based smart waste manage- ment in smart cities Blockchain applica- tions in environmental man- agement	Improved waste management data privacy, scalability and trace- ability	Yes
6	2023	Jin and Chang (2023)	Survey		Citizens participation in envi- ronmental quality monitoring, enhancing transparency	Yes
7	2024	Popescu et al. (2024)	Review	AI-IoT driven technolo- gies for environmental pollution monitor- ing and managemnet	The integration of IoT and machine learning algorithms enhance detection capabilities for various contaminants and providing predictive insights	No
8	2024	Rani et al. (2024)	Survey	Leveraging on blockchain technology is to reduce environ- mental impacts while maintaining security and efficiency	Optimizing supply chains and improving transparency, trace- ability, and accountability in carbon credit and emission trad- ing systems	Yes
9	2024	This Study	Review	IoT-Blockchain in envi- ronmental monitoring and data manage- ment	Convergence-based approach to integrating AI-driven and blockchain-empowered IoT systems is needed for efficient envi- ronmental data monitoring and authenticity	Yes

Table 2 Specific meaning of acronyms

Acronym	Meaning
AI	Artificial intelligence
NH_3	Ammonia
AQM	Air quality management
BC	Blockchain
BCM	Blockchain model
CO_2	Carbondioxide
CECs	Contaminants of emerging concerns
ELISA	Enzyme-linked immunosorbent assay
ESG	Environmental, social, and governance
EPM	Environmental pollution monitoring
GHG	Greenhouse gases
HLF	Hyper ledger fabric
H	Heavy matals
HPL	High-performance liquid chromatography
HRE	Hybrid renewable energy systems
Io	Internet of things
LoRaWAN	low range wireless area network
ML	Machine Learning
NA	Not available
NO_2	Nitrogen dioxide
NZE	Net-zero emissions
PMs	Particulate matter
TVOC	Total volatile organic compounds
VOC	Volatile organic compounds
SO_2	Sulfur dioxide
WHO	World health organization
WSN	Wireless sensor network

Table 3 Review statistics of selected articles

SN	Database	QA	QE
1	IEEE	2	8
2	Elsevier	26	31
3	MDPI	2	6
4	Taylor & Francis	2	2
5	Springer	6	4
6	Wiley & Sons	1	1
7	IGI Global	*	2
8	Frontier	*	1
8	Others (APC, ACS etc.)	3	8
9	Online Reports	1	2
	Total	43	65

- That the publication year of the article falls between 2019 and 2024.
- That the article's primary focus must be on IoT-BC technologies for environmental pollution monitoring.
- That the article's focus is on the modern technology network and a sustainable environment.
- That English is the language in which the article was written and published.

All publications that did not meet the previously stated requirements and considered non-original research were disqualified and deleted from the list of surveyed papers.

Article search result

In the initial phase, 1034 articles were chosen from the designated digital libraries. After eliminating 333 duplicates, 710 articles remained for screening. During the initial screening, 602 articles not meeting the inclusion criteria were excluded. The authors then assessed the full-text eligibility of the remaining 108 articles.

Research type

Qualitative analysis (QA) was conducted on review and survey articles about the use of IoT-BC in environmental monitoring. Insightful information was also gathered from the quantitative analysis (QE) of the data presented in technical papers to satisfy the review objectives and research questions. Additionally, case studies and an online report including data based on evidence on environmental monitoring were taken into consideration, as summarized by the statistics in Table 3.

Background and empirical analysis

Trends in environmental pollution monitoring

Contaminants of emerging concern (CECs) are becoming more common due to the introduction of novel chemical goods by industries for consumption by society (Parida et al. 2021). Wastes from different industries, such as textiles, pharmaceuticals, dye, construction, and soap production companies (Mahmoodi et al. 2020), find their way into the environment. Research has found that pollutants of different origin exist in several samples and environmental compartments in varying amounts, as well as their interactions with various local characteristics, including climate and land use interactions, making air, soil, and water unfit, causing harm to humans and animals. Heavy metals (HMs) are highly toxic and carcinogenic. Mohammadi et al. (2020) reported that the concentrations of lead, cobalt, iron, manganese, and copper in places contaminated by crude oil are noticeably high. Plants in polluted sites absorb HMs like arsenic, zinc (Moutcine et al. 2020), and mercury through their roots from the soil, which through the food chain find their way into human body system.

Furthermore, ongoing industrial and human activities continuously release partic- ulate matter (PM) and microplastics, such as polyvinyl chloride (PVC), polyethylene (PE), and polypropylene (PP), into the atmosphere on daily basis (Zhou et al. 2021; Li et al. 2021a, b). According to a report released by the World Health Organization (WHO), bad air quality contributed to almost 6.7 million fatalities in 2019. Of those deaths, chronic obstructive pulmonary disease (COPD), stroke, ischemic heart dis- ease, lung cancer, diabetes, and asthma collectively accounted for 85% (W.H.O June 25 2024).

Additionally, the release of greenhouse gases (GHG) into the environment adversely affects the health and well-being of living organisms (Singh et al. 2023). The paramount solution for combating carbon dioxide (CO_2) emissions and other GHGs aligns with the Sustainable Development Goal (SDG)-7. Thus, achieving the long-term goal of GHG net-zero emissions (NZE) no later than 2050 by any nation, including the United States, will require implementing significant changes in every aspect of its economy (Xu et al. 2024). This includes strict energy transition laws that promote the use of electric vehicles for transportation, energy efficiency standards, advancements in the industrial and residential sectors as suggested by O¨ zkan et al. 2023. Reducing reliance on fossil fuels, which are major contributors to ecological harm and greenhouse gas emissions, is possible with technological advancements in clean energy sources, including hydroelectricity, wind, geothermal power, and solar energy. In developed countries such as Australia, renewable energy requirements are being emphasized as the world economy grows rapidly (Rahimi et al. 2023) using hybrid renewable energy systems (HRES). Therefore, detailed information about environmental contamination conditions can help researchers, policymakers, developers, and citizens to manage and create a sustainable environment, thereby improving living conditions. This can only be made possible via thorough and data- conscious environmental monitoring strategies.

Empirical findings reveal that the surge in environmental pollution, especially CO_2 and greenhouse gas (GHG) emissions, is a clear indication of lapses in the existing pollution monitoring techniques and technologies. Table 4 highlights the total GHG emissions between 2020 and 2022 in most developed countries of the world.

From Table 4, we can see the steady rise in GHG emissions between 2020 and 2022, with the United States having the highest value of 6017.44 in 2022, closely followed by Brazil with 1310.5, and Japan with 1175.42. These GHG emission values, when compared with their previous values in 2020, question the efficiency claims of modern pollution monitoring techniques and technologies in curtailing environmental pollution and meeting the zero carbon emission target via the deployment of advanced technologies.

For instance, a 3-year percentage increase (2020–2022) in GHG emissions for each developed country in Table 4 can be derived from Eq. (1).

$$\%\Delta_{ghg} = \left(\frac{X_{2022}\prime - X_{2020}}{X_{2020}}\right)x100 \tag{1}$$

where X_{200} = the GHG emission or each country in 2022; and X_{2020} = GHG emission of each country in 2020. The %

Table 4 Total GHGs emissions between the period 2020–2022 and 2022 CO_2 Total Emission for developed countries. Data source Global Atmospheric Research EDGAR 2023

Country	2020 GHG emission	2021 GHG emission	2022 GHG emission	Subtotal	3-Year % increase	Growth factor (GF)	Annual growth rate (CAGR)	% CAG	2022 CO_2 total emission
Units	mton CO_2	mton CO_2	mton CO_2		% Δ_{ghg}			(%)	mton CO_2
United States	5615.57	8923.3	6017.44	20,556.31	7.16	1.07	0.04	3.52	4853.78
Brazil	1277.69	1343.14	1310.5	3931.33	2.57	1.03	0.01	1.28	466.77
Japan	1161.78	1175.42	1182.77	3519.97	1.81	1.02	0.01	0.90	1082.65
Germany	751.34	792.45	784.00	2327.79	4.35	1.04	0.02	2.15	673.60
Canada	711.47	733.08	756.81	2201.36	6.37	1.06	0.03	3.14	582.07
South Korea	699.65	730.84	725.74	2156.23	3.73	1.04	0.02	1.85	635.50
Australia	572.83	561.65	571.38	1705.86	−0.25	1.00	0.00	−0.13	393.16
United Kingdom	407.94	425.71	426.56	1260.21	4.56	1.05	0.02	2.26	340.61
Netherlands	176.88	178.7	167.85	523.43	−5.11	0.95	−0.03	−2.59	134.66
Norway	70.08	71.68	69.97	211.73	−0.16	1.00	0.00	−0.08	42.28
Sweden	62.78	61.41	60.64	184.83	−3.41	0.97	−0.02	−1.72	37.85
Total	11,508.01	14,997.38	12,073.66	38,579.05	4.92	1.05	0.02	2.43	9242.93

Δ_{ghg} values in Table 4 show that the United States, with a 7.16, tops the list of developed countries with the highest increase in GHG emissions between 2020 and 2022. This is followed by Canada with % Δ_{ghg} of 6.37, Germany, 4.35, and South Korea with 3.73. On the contrary, the Netherlands has the lowest % Δ_{ghg} value of -3.41, followed by Sweden with -3.41, and Australia with -0.25 indicating a reduction in GHG emissions between 2020 and 2022.

Furthermore, Eqs. (2) to (4), show the Growth Factor (GF), the annual growth rate (CAGR), and the percentage of annualized growth rate (%CAGR) of GHG emissions between 2020 and 2022.

$$\text{Growth Factor(GF)} = \left(\frac{X_{2022'}}{X_{2020}}\right) \tag{2}$$

$$\text{Annual Growth Rate(CAGR)} = \left(\sqrt{GF} - 1\right) \tag{3}$$

$$\%\text{CAGR} = \text{CAGR} \times 100 \tag{4}$$

The Netherlands has the lowest Growth Factor (GF) of 0.95 and -0.03 annual growth rate (CAGR) between 2020 and 2022, indicating a reduction in GHG emissions. Australia has maintained a 1.00 GF and 0.00 (zero) CAGR between 2020 and 2022. Contrariwise, the United States (3.52%), Canada (3.14%), United Kingdom (2.26%), Germany (2.115%), and South Korea (1.85%) have experienced a significant rise in GHG emissions with an increase in the percentage of annual growth factor rate (% CAGR) of GHG emissions between 2020 and 2022 as shown in Fig. 2.

These empirical analyses and didactic inferences confirm that CO_2 and GHG emissions are a global threat to achieving a sustainable environment. Also, it validates that technological advancements in developing countries have rarely led to GHG emission reduction via the deployment of pollution detection and monitoring framework. A cursory discussion on the threats of CO_2 and GHG emissions in some countries and the strategies deployed to curtail them is necessary.

Carbon and greenhouse gas emission: a global threat

The degradation of greenhouse gases is a slow and persistent process, which has led developed nations, such as Australia, to adopt hybrid energy generation sys- tems that leverage readily available renewable resources like solar, wind, biomass, and hydropower to curb carbon emissions (Rahimi et al. 2023). This approach is widely recognized for its environmentally friendly nature. Over the years, Australia has implemented a hybrid system combining solar photovoltaic (PV) and carbon sequestration (CSP) technology with wind turbines to generate electricity, iden- tifying solar and wind as the most significant renewable resources(Rahimi et al. 2023; Azad et al. 2019). Compared to fossil fuels, this method has proven to have a substantially lower impact on the climate.

The strategy employed by Australia is part of a broader global effort where different countries have developed their carbon emission control policies, each reflecting their specific environmental and economic contexts. For instance, Germany has implemented the"Energiewende" (Energy Transition) initiative, emphasizing a shift to renewable energy sources like offshore wind and solar power (CHen 2024). This initiative is backed by the European Union Emissions Trading System (EU ETS), which sets limits on carbon emissions and enables the trading of emission allowances to incentivize reductions across various industries (Christodoulou and CulLinane 2024). Achieving an 80% share of renewable energy in power production by 2050 is

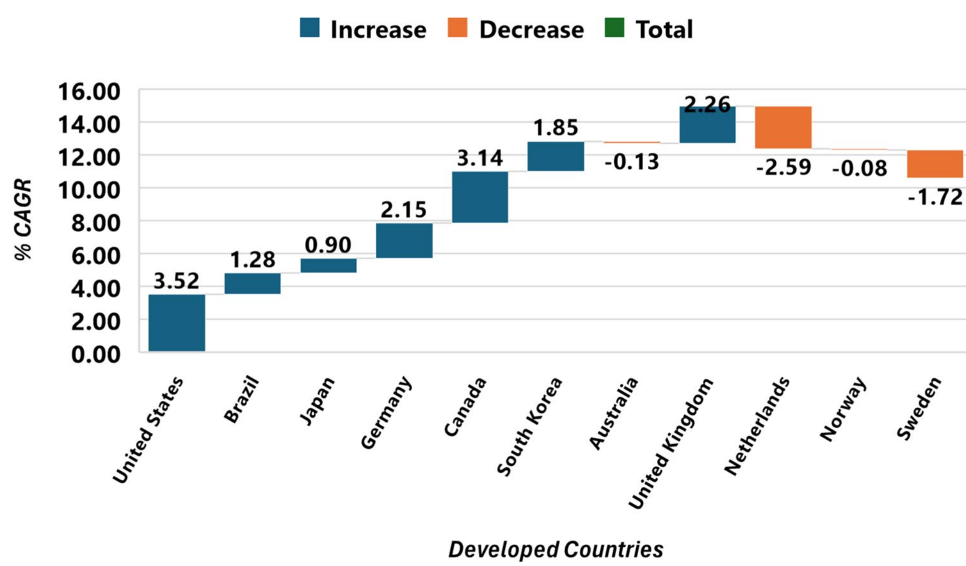


Fig. 2 Percentage of annual growth factor rate (CAGR) of GHG emissions between 2020 and 2022 by European Union

one of the goals of the Energiewende agenda. Also, stricter climate policy laws were implemented in Germany in 2021 to reach net-zero emissions by 2045 and a 65% reduction in GHG emissions compared to 1990 levels (Pata et al. 2024). Similarly, the United Kingdom has implemented its Climate Change Act of 2008, which sets legally binding carbon budgets and promotes nuclear energy as a crucial component of its low-carbon strategy. The UK's efforts are reinforced by the UK Emissions Trading Scheme (UK ETS), a mechanism designed to drive down carbon emissions through market-based incentives.

Total CO_2 emissions between 2020 and 2022 of developed countries as reported by the European Commission are shown in Table 4. The United States currently holds the position as the world's largest consumer of fossil fuels (Depren et al. 2022; Xu et al. 2024) and highest emitter of CO_2 (4853.78mton) followed by Japan, as shown in Fig. 3 with GHG (6017.44mton CO_2eq) (Global Atmospheric Research EDGAR 2023).

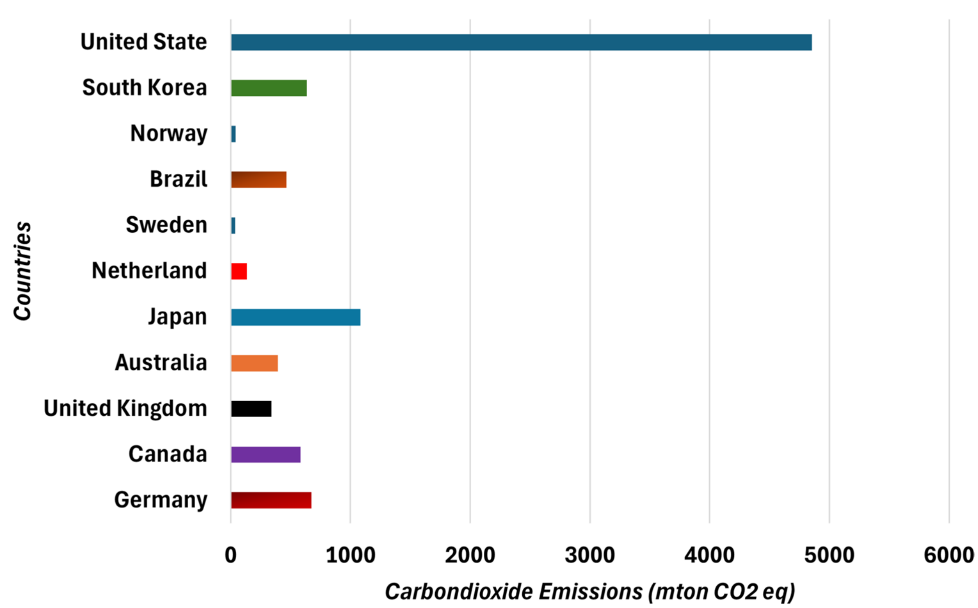
Approximately 79% of the nation's energy in the USA comes from fossil fuels, 12.5% from renewables and 8.4% from nuclear sources. Although wind and solar power are the fastest-growing renewable sources, they currently account for only 5% of the total energy consumption (Xu et al. 2024). This is in contrast to Sweden and Norway which witnessed the lowest CO_2 emission (37.85mton and 42.28mton respectively) in 2022 see Fig. 3. Sweden's total electricity production primarily comprises hydropower, nuclear power, and wind energy. In 2020, the country's gross electric- ity production from various sources included 71,806 GWh hydropower, nuclear power 48,916 GWh, and wind 27,526 GWh being the highest, resulting in 44%, 30%, and 16.9% respectively, of the total production. To achieve the Swedish government's tar- gets for a sustainable energy system, 100% renewable energy by 2040 and net-zero GHG emissions by 2045, nuclear power facilities are planned for gradual phase-out (Jiao and M˚ansson 2023) and to actively utilize wind and solar energy to fully realize the immense potential of variable renewable energy.

Related works

Recent studies emphasize the integration of IoT and BC technologies as a promising approach to advancing pollution detection systems, ensuring a cleaner environment and healthier living conditions for all. For example, Rana et al. (2022) proposed a BC-based IoT framework for monitoring vehicle emissions in real-time, where sensors detect pollutants and transmit the data to a public cloud server, enabling transparency and notifying authorities when emission thresholds are breached. Likewise, Han et al. (2019) introduced a 5G-enabled BC platform for air pollution index measurement, utilizing a multi-layered structure to encrypt data, prevent tamper- ing, and enhance data-sharing efficiency. Addressing water contamination, Lin et al. (2020) developed an IoT-BC framework incorporating GIS tools and wireless sensors to identify pollution sources in real-time. This approach demonstrated strengths in ensuring data immutability and traceability, though it encountered challenges such as computational complexity and limited sensor coverage.

BC applications have also been extended to environmental governance and waste management. For instance, the Blockchain-ESG Integrated (BESGI) framework by Xingbo et al. (2024) leverages Hyperledger Fabric to establish a traceable ESG data management system for

Fig. 3 Top world countries CO_2 emission in 2022



construction projects, achieving cost reductions and enhanced data reliability despite difficulties associated with evolving ESG standards. Similarly, Liu et al. (2022) proposed WasteChain, a BC-enabled system employing smart con- tracts to assess the recyclability of construction waste and assign responsibility to stakeholders. In another study, Zhong et al. (2022) utiLized permissioned BC architectures integrated with IoT sensors to monitor construction pollutants, automate environmental performance assessments, and maintain data integrity. FurtHermore, Niya et al. 2018 suggested a decentralized LoRaWAN-based system with Ethereum blockchain for air and water quality monitoring, addressing high power consumption and ensuring data authenticity without reliance on trusted third parties.

These initiatives emphasize the potential of BC and IoT in environmental manage- ment, while also highlighting the need for further refinement and practical validation. With the empirical findings in Table 4 revealing a significant rise in CO_2 and GHG emissions, it is necessary to assess in detail the dynamics and peculiarities of deployed contaminants monitoring and detection frameworks.

Evolving contaminants detection techniques & use case

Over the years, the approaches explored by experts in monitoring and analyz- ing environmental pollution parameters have evolved in response to technological advancements and societal development. Figure 4 highlights the trends in EPM tech- nologies, case studies, and their peculiarities; ranging from traditional techniques to convergence-based approaches. An assay of the EPM methods is discussed forthwith.

Traditional/conventional frameworks

Several traditional EPM approaches have been adopted to track contaminant data. Among the notable methods include

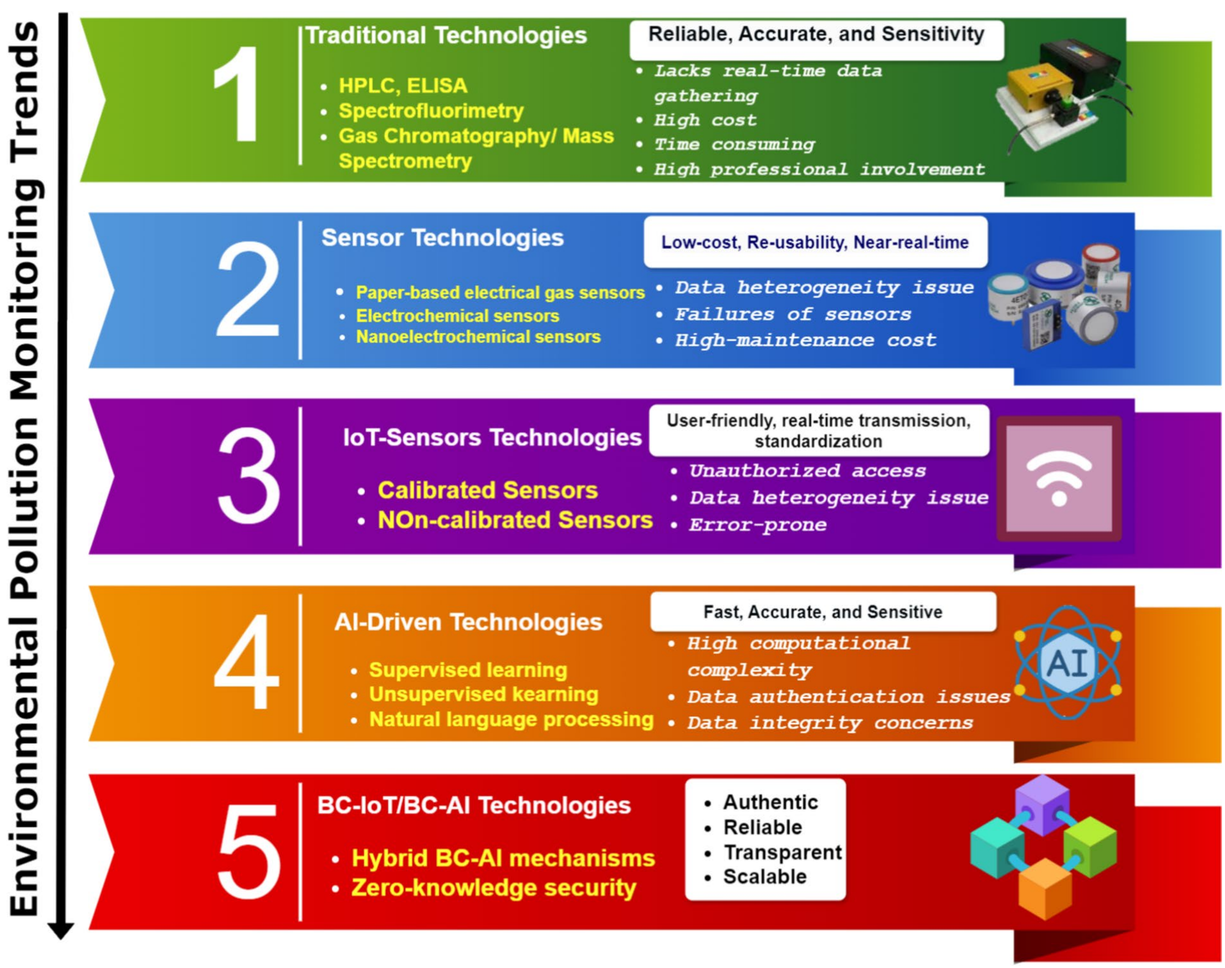


Fig. 4 Trends in environmental pollution monitoring technologies, highlighting the developmental stages and characteristics

Enzyme-linked immunosorbent assay (ELISA), spectrofluorimetry, high-performance liquid chromatography (HPLC), Gas Chro- matography/Mass Spectrometry, etc. Firstly, according to the traditional approaches, pollutants such as total volatile organic compounds (TVOC), formaldehyde, tetra- chloroethylene, xylene, and 1,3-butadiene (Vallecillos et al. 2024), particulate polycyclic aromatic hydrocarbons (PAHs) (Pietrogrande et al. 2023) can be detected and monitored using gas chromatography-mass spec- trometry. This was successfully applied by Pietrogrande et al. (2023) to analyze the presence of particulate PAHs in ambient air samples collected at an urban polluted site. A solid phase extraction (SPE) cartridge, utilizing a molec- ularly imprinted polymer (MIP-SPE), was employed, specifically designed for the selective retention of PAHs with four or more fused benzene rings.MIP-SPE demon- strated an extraction recovery of nearly 95% for heavier PAHs, ranging from 5–6 ring benzo(α)pyrene and benzo(ghi)perylene, and 90% for PAHs with four benzene rings, exhibiting good reproducibility (RSDs: 2.5–5.9%). Data acquisition for PAHs was conducted using the Thermo Scientific 1.4 X-Calibur program (Pietrogrande et al. 2023).

In addition, using HPLC method by Wo´zniak et al. (2023), a mass concentration of nylon 66 microplastics (MPs) ranging from 0.30 to 4.37 ngm^{-3} was reported to be present in the inhalable fraction of particulate matter collected in a shopping complex (Patnana et al. 2024).

Furthermore, ELISA is a simple and cost-effective biochemical technique that can quantify environmental contaminants, pathogens, and pollutants (air, land, sea). ELISA is rapid in screening environmental samples. To justify this assertion, the U.S Geological Survey (USGS) deployed it to verify the quality of samples of drinking water in 67 public water systems in Minnesota. The results indicate that ELISA successfully detected most of the contaminants in the water, including three pesti- cides (atrazine, pyrethroids, and imidacloprid) and/or three pharmaceuticals (caffeine, sulfamethoxazole, and carbamazepin) (Krall et al. 2022).

These conventional procedures are commendable, reliable, accurate, and sensitive, especially ease of deployment in tracking EPM data. However, real-time quality envi- ronmental data with reasonable temporal and spatial resolutions cannot be obtained cheaply using traditional monitoring methods. Other notable drawbacks include labor-intensive, high-cost, and time-consuming sample collection, pre-treatment, and preparation, which require highly professional skills. To overcome the limitations of traditional EPM methods, sensor-based technologies were introduced.

Sensor-based frameworks

Over few decades, the research field has witnessed a significant increase in the deploy- ment of low-cost sensor technologies for monitoring environmental quality (Fanti et al. 2021) to mitigate the drawbacks of traditional methods. Notable among the sensor- based EPM approaches are paper-based electrical gas sensors, electrochemical sensors, and nano-electrochemical sensors.

Gallego et al. (2023) developed gas sensors to continuously monitor volatile organic compounds (VOC) concentrations in outdoor air. Two sensor sta- tions, equipped with sampling pumps, were placed in a polluted area. The stations began recording data continuously from two different types of VOC sensors, along with temperature, pressure, and relative humidity, at 1.5 min intervals. To connect the monitoring equipment locations to the online data reception server, data including atmospheric parameters, VOC concentration levels, and sampling parameters (such as sampling status, flow rate, and volume) were transmitted (Gallego et al. 2023). Paper-based electrical gas sensors (PEGS) were used to detect water-soluble gases, including carbon dioxide, ammonia, and trimethylamine (Barandun et al. 2019). Using a two-step in situ oxidation process, Sun et al. 2023 developed the PANI-NiC_2O_4 nanocomposite on nickel foam, which was utilized as electrochemical sensor, sensitive for monitoring dissolved ammonia. The self-supported PANI-NiC_2O_4 electrode demonstrated excellent dissolved ammonia detection capability, with a sensitivity of 41 mA μM^{-1}Cm^{-2} and a limit of detection (LOD) of 0.83 μM in the concentration range of 0.1–1 μM. The reusability, repeatability, anti-interference properties, and sensor's stability were evaluated, demonstrating outstanding performance (Sun et al. 2023). The performance of PEGS, which largely offers qualitative data, is highly influenced by relative humidity levels. Also, electrochemical sensors are used The signal generated depends on the analyte concentration (He et al. 2023). By adding chemical or biological substances to the electrode matrix, the electrochemical properties improve (He et al. 2019a; Nganda et al. 2023). Also, the use of nano-electrochemical-based sensors was reported by He et al. (2023); Nganda et al. 2023. Apart from the optical, thermal sensors, and mass, the electrochemical sensors captured the attention of researchers due to their cost- effectiveness, detectability, and ease of experimentation (He et al. 2019b). The electrochemical approach to be used depends on the target signal to be measured. Voltammetry is an electrochemical technique that uses current–voltage curves to quantify current at different potentials. The most commonly used reliable tools, known for their accuracy and high sensitivity in measuring trace levels of significant environmental contaminants, include differential pulse voltammetry (DPV), linear sweep voltammetry (LSV), square-wave voltammetry (SWV), cyclic voltammetry (CV), and stripping voltammetry (Barhoum et al. 2023). However, the integration of nanotechnology and polymer nanocomposites (PNCs) has made the techniques a sophisticated one for contaminants control and analysis. For CO_2 monitoring, Manzoor et al. (2022) developed and studied a smart sensor based on SWCNT functionalized with polyethyleneimine and starch (PEI-starch). Meanwhile, Oh et al. 2021 investigated the LaNiSbWO4-graphene-PPy nanocomposite, which features stacked layers of LaNiSbWO4-G-PPy as sensing electrode materials for ambient CO_2 gas monitoring. The deployment of a sensor-based approach to track EPM data brought about data re-usability, near-real-time data monitoring, and low-cost system integration.

Albeit, sensor-based frameworks are confronted with data heterogeneity, incessant sensor failures, and high-cost system maintenance, amongst other issues.

IoT-sensors frameworks for real-time EPM

To address the issues in the sensor-based approach, the IoT was integrated into the EPM framework for real-time data tracking as captured in Table 5. IoT has become the foundation for the development of smart cities (Ashraf 2021; Salman and Hasar 2023). It is now practically useful due to the annual increase in internet connectivity around the world, connecting billions of gadgets and city dwellers, particularly in smart cities (Sarwesh and MatHew 2022; Abad´ıa et al. 2022). Reducing pollution at its source and raising people's knowledge of environmental issues can be accomplished through monitoring the actions contributing to pollution. Currently, digital technologies, such as the long-range Internet of Things (LoRa IoT), are having a profound impact on the development of smart infrastructure aimed at achieving environmental sustainability (Rana et al. 2022).

IoT sensors can be categorized into calibrated and non-calibrated sensors (Han et al. 2019). Calibrated are employed to measure exert levels of PM in the environment, including hydrogen (H_2), fine dust, phosphine (PH_3), and sulfur dioxide (SO_2). Non-calibrated sensors, on the other hand, are used to monitor the release of PM in the air, such as ammonia (NH_3) and nitrogen dioxide (NO_2) (Ajakwe et al. 2022; Han et al. 2019). All these substances should be closely monitored because they are hazardous to the human system even at low concentrations (Kumar et al. 2018). The technology's low-cost and user-friendly sensor nodes are a huge benefit in smart cities, particularly regarding environmental aspects. Users may access real-time environmental factor data monitoring and control using sensor nodes, which can detect and assess changes in ecological parameters including temperature, pressure, and gases (CHeng et al. 2022; Salman and Hasar 2023).

Despite the significant potential of IoT-Sensor-based EPM approaches, unautho- rized access to sensitive environmental data, data falsification, data heterogeneity, etc., remains its downside. Hence, the IoT-Sensor approach is confronted primarily with data security issues which ultimately cast doubts on the validity and authenticity of the EPM data used in most systems and its source. A security architecture that can guarantee maximum EPM data security while leveraging real-time data transmission via IoT-Sensor integration becomes necessary.

IoT-blockchain frameworks

Understanding blockchain technology

BC is an international network of computers that disseminates, authenticates, and upholds a database of transaction records (Saberi et al. 2019). Bitcoin is a widely known

Table 5 Current Trend of IoT-BC Framework in Environmental Monitoring

References	Proposed framework	Parameters	Environment	Benefits	Drawbacks
Rana et al. (2022)	LoRa BC-IoT system	PM_{10}, $PM_{2.5}$	Air	Low energy consumption	NA
Han et al. (2019)	5G-wireless- BC	API measurement	Air	Real-time data control	NA
Lin et al. (2020)	WSN-DAG BC-IoT	Copper	Water	Data traceability, immutability	Limited sensors
Xingbo et al. (2024)	BESGI with HLF	ESG indicators	Industry	Feasibility, data robustness traceability, 20% reduced labour cost	Constant expansion of ESG standard
Liu et al. (2022)	BeCW with smart contracts	Construction wastes	Construction wastes	Unified and explicit referencing system, data reliability	Requires further validation
Zhong et al. (2022) Androulaki et al. (2018)	Permissioned BC with HLF	Noise, PM	Air	Smart contract automation	Transparency at risk due to HLF
Niya et al. (2018)	LoRaWAN with ELC	Air/ Water parameters	Air, water quality	Completely decentralized No TTP	NA

example of a blockchain application. It is a digital ledger connected to a distributed network that is mined, stored, and traded using an advanced computer algorithm. According to Seebacher and Schu¨ritz (2017), BC is defined as a decentral- ized database managed by a peer-to-peer network, consisting of a linked sequence of blocks. Each block contains timestamped transactions that are secured by public-key cryptography (referred to as "hash") and verified by the network community. Once a transaction is added to the BC, it cannot be altered, thus transforming the BC into an immutable record of past activities (Al Sadawi et al. 2021) as shown in Fig. 5.

In both the financial and non-financial sectors, BC technology has been recognized as a promising innovation and catalyst (Wang et al. 2019) in areas such as academia, food production tracing (Caro et al. 2018), industrial manufacturing, supply chains (Saberi et al. 2019), the environment, healthcare and medical data (Dwivedi et al. 2019), and proposed for identification of irrigation water pollution sources (Lin et al. 2020).

BC technology, which was created as a transaction processing system, stands apart from other systems due to its special characteristics, which include decentralization, transparency, immutability, consensus-building, secure data storage, and intelligent smart contracts (Al-Sulami et al. 2024; Guo and Yu 2022). These qualities make it a potentially trustworthy platform for environmental monitoring (Zhong et al. 2022) and other domains (Ajakwe et al. 2023) . BC technology has proven to be resilient against hackers, unlike most companies that store their data in centralized databases (Pieters et al. 2021; Sarmah 2018). By digitally stamping each transaction, BC users can easily trace the history and ori- gin of every transaction. The peer-to-peer structure of BC enhances its resistance to cyber-attacks. Additionally, all transactions and information are visible to any node within the network (Al Sadawi et al. 2021). With BC-based applications, environmen- tal pollution data from different sources cannot be manipulated by the organization or any stakeholder member. Hence, the authenticity of such data can be reliable for environmental interventions, research, and collaboration purposes.

IoT-BC potentials in securing EPM data

An innovative approach to the problems of data management and environmental pollution monitoring is provided by combining BC and IoT technology. This strat- egy uses BC's strong capabilities for guaranteeing data integrity, traceability, and transparency as well as IoT's capacity to offer real-time monitoring of environmental parameters using inexpensive, scalable sensors (Lin et al. 2020). By integrating these technologies, the framework reduces the possibility of data manipulation, improves the accuracy of pollution detection, and streamlines stakeholder accountability. Imple- menting lightweight frameworks has great promise for creating a sustainable and environmentally friendly future, despite obstacles such as high computing complexity and sensor limits (Rana et al. 2022; Lin et al. 2020).

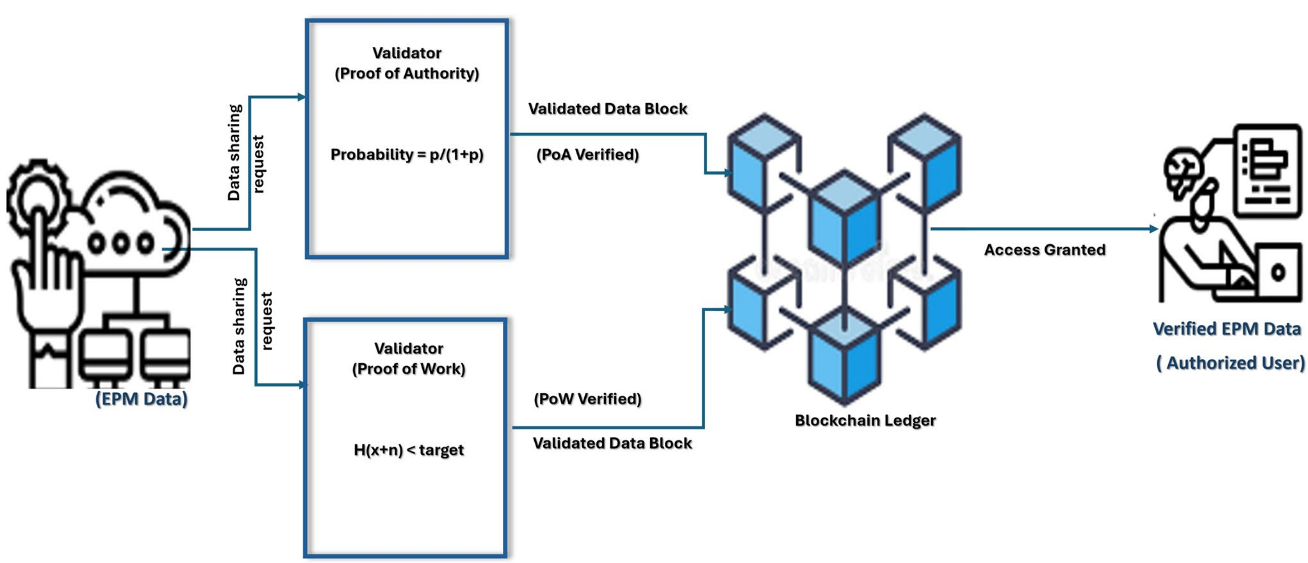


Fig. 5 The process of validating EPM data in a blockchain network using consensus algorithms

Comparative analysis of convergence of IoT-BC for pollution monitoring

The United Nations (UN) 2030 agenda states that to establish fresh air and ensure a healthy life for all living things, the pollution detection system must be enhanced (Rana et al. 2022). This section explores the current trends in the IoT-BC techniques used by environmental experts in pollution detection and data management to achieve the UN agenda. Table 5 captures the details of some of the specific use cases.

Rana et al. 2022 proposed a long-range IoT-BC system (LoRa BC-IoT) for real- time vehicle pollution monitoring. This system integrates hardware with the BC network and includes authentication of nodes. The pollutant sensors are connected to the vehicle with internet availability. When the vehicle starts, sensing of emission data starts as summarized in Table 6.

The sensors gather data on the emission levels of various pollutants. The sensors' readings in real-time are logged on a cloud server through the sensor node and gateway, with the monitoring process occurring in the public domain. Data can be accessed from the cloud server via a web app or mobile application. It was observed that PM2.5 and PM10 levels were elevated (Rana et al. 2022). If the vehicle's data continuously exceeds the threshold for a set time, the owner and the traffic police department will be notified. The pollutant contents of the location were monitored at different times in intervals of 24 h. Results were captured at 12:30 pm. Though the authors did not mention any known drawbacks and inefficiencies in their proposed system, the empirical result gives credence to it as a worthwhile effort in realizing zero-carbon reduction via secured EPM data management. However, the details of the adopted BC network and consensus algorithm are unknown.

Han et al. (2019) proposed a 5G-wireless-BC platform, which utilizes a 5G wireless network and BC to prevent data forgery and tampering through the data preservation layer. BC technology was employed to encrypt and transmit data to the cloud, facilitating real-time air pollution index measurements. The system's overall architecture consists of five layers: the perception layer, the data processing layer, the 5G wireless network layer, the data preservation layer, and the application layer, which includes storage devices and analysis tools, along with services such as configuration, reporting, and authentication. The encryption technology of BC and the distributed messaging protocol enhance data processing efficiency, enabling data sharing while ensuring data integrity.

Table 6 Air quality monitoring using LoRa BC-IoT Model Rana et al. 2022

Pollutant content	Values (24 h)	Air quality (Range)
PM_{10}	> 100	Moderate (101–250)
PM2.5	= 100	Poor (91–120)
NO_2	above 10	Good (0–40)
O_3	above 20	Good (0–50)
CO	1	Good (0–1.0)

To track the source of water contamination in real time, (Lin et al. 2020) employed an integrated framework (WSN-DAG-BC-IoT) built on BC technology and the IoT. It includes GIS tools, a wireless sensor network (WSN) structured using a directed acyclic graph (DAG), and two sensors (a regular sensor and an automatic heavy metal sen- sor). GIS and BC technologies were utilized to locate dirty units upstream and track pollution at mapped irrigation units. Among the pollutants (Cd, Cu^{2+}, Zn, Ni, Pb) and other factors (pH, temperature, Electrical Conductivity (EC)) monitored, EC and Cu^{2+} were rapidly identified. Through the backward pollution source tracing (BPST) process, the Water Quality Analysis Simulation Program (WASP) model successfully simulated EC and Cu^{2+} concentration data to identify potential pollution sources.

The data was managed within a peer-to-peer network for inter-node communication, ensuring its immutability. The model is beneficial for data traceability and immutabil- ity and suitable for multiple types of pollution. However, the issue of computational complexity arises, and due to the limited number of sensors—potentially caused by budget constraints—the upstream-to-downstream irrigation units were fixed in a basic spatial arrangement, employing the"design science research method (DSRM)" (De Sordi and De Sordi 2021).

To identify data sources and give access to secured and crucial environmental, social, and governance (ESG) information, Xingbo et al. (2024) developed the Blockchain-ESG Integrated (BESGI) framework, which identifies ten architecture, engineering, and construction (AEC) ESG indicators and provides a mapping mech- anism to align these indicators with construction projects. The framework utilizes Hyperledger Fabric 1.4.0, a blockchain-based data management technique, to create a traceable ESG data management system within the BESGI framework. The result from deploying the BESGI framework for EPM data management is summarized in Fig. 6.

The results demonstrate that the framework is feasible and can reduce labor costs by 20.15% in comparison to traditional ESG management methods. Also, data upload was fast using BESGI framework, with 103 h of simulation time as against slow data upload in the traditional approach and 129 h of simulation time. The pro- posed model offered significant advantages in terms of traceable ESG data within AEC industry projects and enhanced the robustness of the data (Xingbo et al. 2024). However, the paper acknowledges

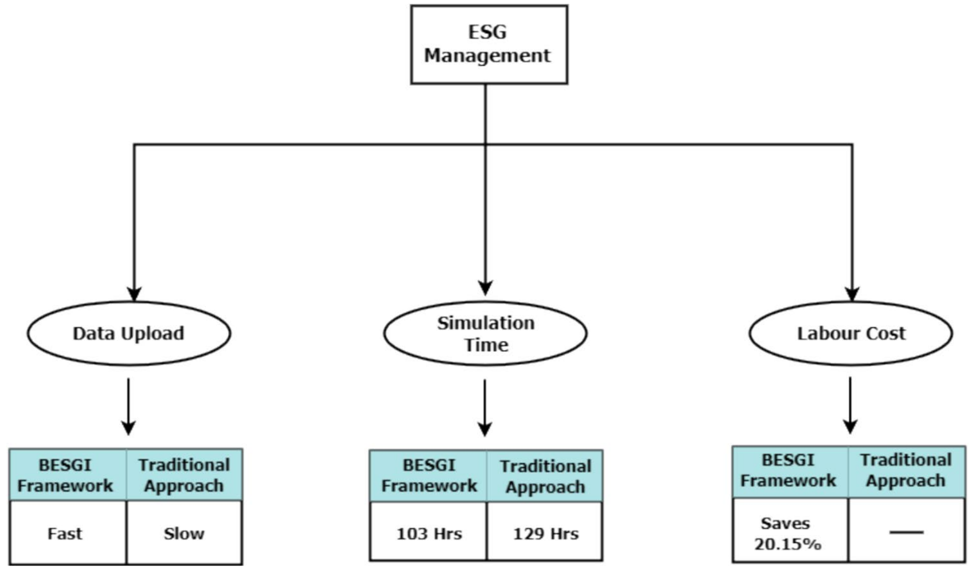


Fig. 6 Environmental, social, and governance (ESG) data management findings (Xingbo et al. 2024)

some limitations, such as the continuously growing range of international and local ESG standards. As a result, the precise identification of ESG data still requires manual intervention.

Additionally, a BC-enhanced conceptual framework for construction waste infor- mation management (BeCW), designed to support sustainable urban development, was proposed by Liu et al. (2022). The framework integrates a WasteChain to provide stakeholders with a reliable credit system for assessing the recyclability of building waste. This is facilitated through BC technology and self-executing smart contracts, which clarify the responsibilities and ownership of relevant stakeholders. While the system offers a unified and transparent framework for referencing, it may require additional testing and validation for further improvement.

Furthermore, Zhong et al. (2022) utilized the Hyperledger Fabric (HLF) architec- ture, an open-source, modular, and extensible system for implementing and managing permissioned BC, for environmental monitoring on construction sites. HLF can be con- sidered a permissioned BC that ensures authorization through the Fabric Certificate Authority (Fabric-CA) and Membership Service Provider (MSP). The MSP provides all peers participating in the BC network with identities (Androulaki et al. 2018). Data collected from various IoT sensors, such as noise and PM sensors, were first integrated with a cloud platform before being uploaded to a decentralized BC network, replacing the need for centralized databases or servers. Smart contracts were automatically programmed to monitor the levels of construction pollutants and check the evaluation performance. The noise data, collected over a specific period, showed that noise lev- els at the construction site were generally stable at 50 dB, with an alarm triggered at 11:40 am when the noise level reached 66.4 dB. The proposed technique is more energy-efficient and easier to implement compared to permissionless blockchain archi- tectures (Kuzlu et al. 2019). Moreover, the data can be accessed by each node and is protected from tampering, ensuring that participants can trust the information (Zhong et al. 2022). However, the framework faces a limitation due to HLF being a"private and permissioned" BC, which raises concerns about decentralization, transparency, and participant equality.

Finally, Niya et al. (2018) proposed a distributed system for automatic measurement, storage, and monitoring of air and water quality in the environment that implements the LoRaWAN protocol. LoRa addresses the issues with IoT protocols' high power consumption and long-range transmission. By utilizing the Ethereum BC to store and access data captured by IoT sensors, the architecture became fully decentralized, elimi- nating the need for a Trusted Third Party (TTP) to ensure data integrity. The methods employed in this Pollution Monitoring System (PMS) enable users to automatically retrieve information collected by IoT devices and transfer it to the Ethereum BC. This data can then be used to substantiate the presence of pollution in the observed area. The inherent limitations of the IoT-BC frameworks have led to hybrid and advanced technologies integration in EPM data management.

Integrating advanced technologies into hybrid renewable energy systems, HRES

HRES integrates multiple renewable energy sources, such as solar, wind, biomass, and hydropower, to optimize energy production, improve system reliability, and address the intermittency challenges typically associated with each individual energy source. The integration of advanced technologies, particularly AI (CHander and Gopalakrishnan 2024; Ajakwe et al.2022), IoT, and BC has significantly improved the efficiency, scalability, and sustainability of these systems (Mengelkamp et al. 2018; Ajakwe et al. 2024a, b).

Table 7 demonstrates that the incorporation of AI algorithms enhances the pre- diction of energy production and consumption trends, optimizes energy storage, and improves decision-making in energy distribution. Machine learning models can process large datasets from various sensors to predict weather patterns, thereby increasing the reliability of solar and wind energy sources (Mazzeo et al. 2021). IoT devices enable real-time monitoring and management of energy systems. By collecting energy gen- eration, storage levels, and consumption data, IoT enables proactive maintenance, reduces downtime, and ensures optimal HRES performance. BC provides a secure and transparent platform for managing energy transactions within HRES. It ensures data integrity, enables peer-to-peer energy trading, and improves the traceability of energy sources, fostering trust and accountability (Li et al. 2019; Yang et al. 2021). These advancements collectively demonstrate the global commitment to enhancing renewable energy systems and reducing GHG emissions, thereby monitoring pollution through technological innovations.

Open issues and future directions in EPM data management

Open research issues

Despite technological progress in securing environmental data, the inherent issues still demand re-inventing the wheel for a safe, secure, and sustainable environment. These research issues can be summarized as leakages in data transmission, loop-sided data poisoning processing, latency-aware data security schemes, lax-cryptic trustworthiness, and lean BC applications.

Leakages in data transmission

First, multiple heterogeneous environmental data, including air quality index, are constantly being generated, such as meteorological parameters (temperature, relative humidity), pollutants' concentration parameters, seasonal variations (Kayes et al. 2019; Gallego et al. 2023). The EPM data from these interconnected sensors and edge devices at different nodes/locations are constantly exposed to vulner- abilities and can be intercepted and manipulated by unauthorized users due to lapses in existing data security architecture. Hence, a need for data traceability, authenticity, and transparency during transmission and storage. This is to mitigate unauthorized access to sensitive environmental data as well as curtail security breaches, which can be detrimental to the sustainability of an eco-friendly environment (Simeon Okechukwu Ajakwe, Ajakwe, et al. 2023).

Table 7 Advanced technologies in hybrid renewable energy systems

References	Integrated Tech-	Contribution
Mazzeo et al. (2021) Sankarananth et al. (2023) Chander and Gopalakrishnan (2024)	Artificial Intelligence (AI)	Predictive and Forecasting solar and wind energy availability, Balancing renewable energy demand and supply, Optimization of energy storage and distribution, Reducing operational costs
Li et al. (2019) Yang et al. (2021) Xu et al. (2021)	Blockchain	Secure energy transactions Peer-to-peer energy trading Enhancing data transparency and security
Khan et al. (2023) Sai Ganesh et al. (2022)	AI-Blockchain	Distribution optimization and controlled monitoring in a secure manner Automation of power distribution in smart grids Proper structure of consumer billing/usage Data integrity, transparency
Mahesh et al. (2024) Codon et al. (2023)	IoT- Blockchain	Real-time monitoring of energy systems Automated control of energy flows Data collection for performance analysis Efficient energy management practices

Loopsided EPM data poisoning

Secondly, since the multiple sensors transmitting EPM data are placed at different locations of the environment (land, air, and sea) and are connected over IoT, the possibility of injecting false EPM data is very high (Ajakwe et al. 2024; Huang et al. 2024). Usually, false data can be injected into an IoT system via different means such as cross-scripting, exploitative means, man-in-the-middle (Huang et al. 2024). In most cases, these falsified data are deployed in precision- sensitive systems such as environmental pollution monitoring systems without being aware of their inconsistencies and inaccuracies until the results are obvious during the decision-making. Therefore, a standardized approach to checking EPM data quality to forestall data poisoning remains a challenge. Ultimately, falsified data used to conduct an accurate analysis using the right methodology will produce a falsified result (Ajakwe et al.2024).

Latency-aware data schemes & limited sensors

Thirdly, most existing IoT-BC frameworks for environmental data monitoring have high computational complexity problems and use few sensors (Lin et al. 2020), which are inadequate for monitoring and measuring the required pollutants. This inadequacy of sensor parameter measurements leads to biased result analysis, hypothetical suppositions, and unfounded conclusions.

Lax-cryptic trustworthy process

Fourthly, existing BC-based frameworks are not explicit in the types of BC networks used as well as the underlying consensus algorithm deployed. This indicates vagueness and lack of trustworthiness in the security capacity of these systems in guaranteeing qualitative monitoring and control of environmental data, which is of crucial importance. The ambiguity present in the current EPM IoT-BC frameworks raises concerns about the accuracy and reliability of the processes that produced their results.

Lean application of BC in EPM

Finally, the potential of BC technology applications for investigating and manag- ing environmental data has not received much attention (Zhong et al. 2022). This is because BC technology adoption is still nascent in the environmental biochemistry domain. Subsequently, there are more review articles than technical papers on the subject matter. Addressing these issues requires a convergence-based approach to inte- grating AI-driven and BC-empowered IoT systems for efficient environmental data monitoring.

Future directions in EPM data security

The futuristic EPM system that will deliver precise, reliable, and secure results will incorporate connected innovation intelligence (Ajakwe et al.2022) in its design to address contemporary and emerging issues. Figure 6.1.4 highlights the inter- connection of IoT-BC security with human-understandable AI-empowered logic for a rewardable green energy environment that encourages minimal pollution via secured user data monitoring and management.

To address the challenge of heterogeneous data generation, Xingbo et al. (2024) proposes exploring the potential of natural language processing (NLP) solutions. These solutions facilitate accurate and automated ESG data management by developing multimodal machine learning mechanisms to process multivariate heterogeneous data, contributing to advancements in environmental data management (Xingbo et al. 2024). However, AI-driven processes are insecure. Hence, there is a need to secure the cog- nitive engine that interprets the data, a function performed by incorporating BC. Thus, with an NLP-BC approach, the environmental data source traceability and authenticity are guaranteed (Fig. 7).

In addition, to address computational complexity issues, Lin et al. 2020 recom- mends that lightweight and cost-effective IoT-BC frameworks be developed to handle multiple data emanating from various monitoring edge devices. This cost-effectiveness ensures that low-cost sensors that are scalable are mounted on customized IoT-based systems (Rana et al. 2022) to capture all environmental pollution parameters. This ensures a speedy and robust evaluation of parameters and transactions in the framework. Thus, research efforts directed in this area are highly solicited.

Furthermore, there is a need to integrate and deploy different BC networks (pub- lic, private, and consortium) to secure and monitor environmental pollution data depending on the given implementation instance. Also, to maintain a balance between security, scalability, and speed of authenticating environmental data transactions, environmental engineers and designers should be explicit in the choice of the consen- sus algorithm selected for the IoT-BC system. This is to ensure transparency in the reproducibility of research.

Moreover, a convergence-based research and implementation approach to address- ing issues associated with the dynamic nature of environmental data is recommended (Zhong et al. 2022). This approach will enable the design and implementation of frameworks for specific case studies, along with the development of cost-effective construction waste information management software packages (Liu et al.

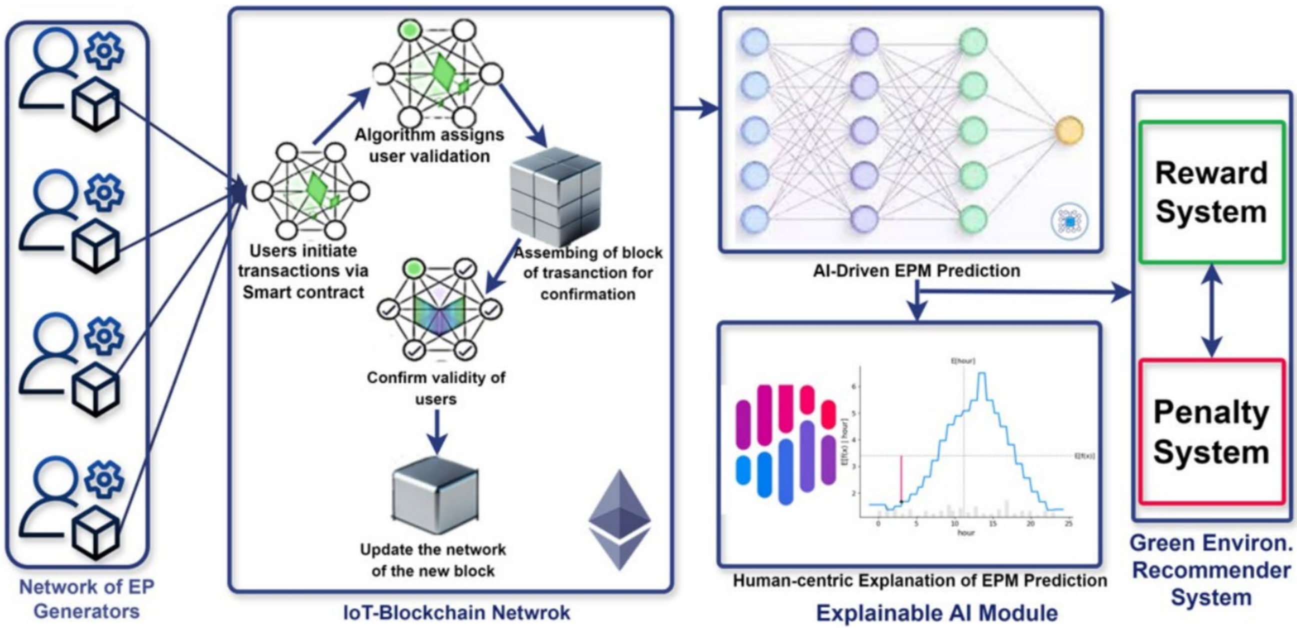


Fig. 7 Recommender system for sustainable EPM data management highlighting the interface of blockchain for participants validation and explainable AI for human-understandable predictions

2022). Additionally, it will contribute to reducing implementation costs, optimizing technical performance, and enhancing the practical benefits of proposed frameworks for efficient and secure environmental data monitoring.

In addition, the future of HRES lies in the continuous integration of advanced technologies. Emerging trends suggest a move towards more autonomous energy sys- tems that leverage AI for real-time decision-making, IoT for seamless connectivity, and BC for secure and transparent operations. Also, the convergence of these approaches can result in the creation of smart energy grids that are self-healing, optimize energy distribution, and support sustainable energy practices on a broader.

Finally, incorporating “Green Coin” technology into the existing frameworks can offer new environmental monitoring and sustainability avenues. Green coins, leveraging BC’s transparency and security, incentivize eco-friendly behaviors by rewarding indi- viduals and organizations for actions that contribute to ecological preservation. When integrated into HRES, green coins can motivate stakeholders to adopt sustainable practices, support renewable energy projects, and engage in carbon reduction initiatives (Alzoubi and Mishra 2023). For instance, users generating excess renewable energy can earn green coins through blockchain-enabled platforms. These coins can then be traded or used to purchase additional energy, creating a sustainable economic model that aligns with environmental goals. This symbiotic relationship between cutting- edge technologies and incentive mechanisms, such as green coins, has the potential to greatly expedite the transition to a low-carbon future.

Conclusion

An in-depth understanding of environmental contaminants and scenarios helps researchers, industries, government, and individuals to create and manage a sustainable environment, which improves living circumstances. This review examined the various techniques and technologies used in environmental pollution monitoring and data storage management; from the conventional to convergence-based IoT-BC approaches.

The findings revealed that in preserving data integrity, BC’s distributed messag- ing system and encryption technology increased the effectiveness of data processing and allowed for data exchange, thereby addressing some of the inherent lapses in the conventional approaches. Also, data was maintained immutably by inter-node communication via a peer-to-peer network. The concept is useful for immutability, data traceability, and suitability for various pollution types. However, integrating blockchain technology into environmental pollution monitoring is nascent and is confronted with issues such as data transmission leakages, data poisoning, high computational complexity, cryptic trustworthiness, and others. Futuristic EPM data management systems advocate the incorporation of connected innovation intelligence that leverages the convergence strategy of BC-enabled, AI-driven, and IoT-empowered systems for effective environmental data monitoring.

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Declarations

Ethical approval This article does not contain any studies with human participants or animals performed by any of the authors.

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