Research Square

Preprints are preliminary reports that have not undergone peer review.
They should not be considered conclusive, used to inform clinical practice,
or referenced by the media as validated information.

Quantum Computing for Climate Variability Monitoring in Wetlands and Drylands: PRISMA Systematic Review

Madyembwa Monica

mmadyembwa@gzu.ac.zw

Great Zimbabwe University

Nyerai Itai

Great Zimbabwe University

Hungwe Tinoziva

Great Zimbabwe University

Hardlife Zinhiva

Great Zimbabwe University

Research Article

Keywords: Climate variability, Quantum computing, Environmental monitoring, Wetland ecosystems, Dryland ecosystems

Posted Date: November 13th, 2026

DOI: https://doi.org/10.21203/rs.3.rs-11293247/v1

License: This work is licensed under a Creative Commons Attribution 4.0 International License.
Read Full License

Additional Declarations: No competing interests reported.

Abstract

Climate variability is increasing the frequency and intensity of droughts, floods, and changing rainfall patterns, threatening the sustainability of wetland and dryland ecosystems. These ecosystems are highly sensitive to climatic changes. However, conventional monitoring approaches remain constrained in their ability to efficiently process large and heterogeneous datasets. They also face challenges in integrating diverse environmental data and accurately representing complex ecosystem interactions. This study aimed to systematically review the potential of quantum computing for climate variability monitoring in wetland and dryland ecosystems. A systematic review of studies published between 2017 and 2026 was conducted using Google Scholar, Web of Science and ScienceDirect databases The systematic literature search identified 120 records (ScienceDirect = 52; Web of Science = 27; Google Scholar = 41). Duplicate records (28) were removed and 92 records remained for title and abstract screening. During the screening stage, 56 articles were excluded for not meeting the predefined inclusion criteria. Therefore, 36 were assessed for eligibility of which 19 studies were excluded for lacking sufficient methodological detail. Consequently, 17 studies satisfied all inclusion criteria and were included in the qualitative thematic synthesis. The reviewed studies highlighted significant limitations in conventional modelling approaches. Quantum computing was identified as an emerging technology with the potential to enhance climate simulations, pattern recognition, optimization, and predictive monitoring of vulnerable ecosystems. It has the potential to complement existing environmental monitoring approaches by improving computational efficiency and supporting more accurate climate prediction.

1. Introduction

Climate variability is no longer viewed as a series of isolated weather events. Instead, it is understood as a complex environmental systems challenge (Rajeena et al., 2026). This challenge influences interconnected ecological, hydrological, and atmospheric processes. The rising temperatures, changing rainfall patterns, prolonged droughts, intense floods, and shifting seasonal cycles interact in complex ways (Kashem, 2025). These interactions increase climatic uncertainty. Instead of producing single environmental disturbances, these changes often generate compound climatic events whose effects spread through ecosystems. Prolonged drought can reduce vegetation cover, expose soils to erosion, lower water availability, and ultimately affect biodiversity and ecosystem productivity (Moss et al., 2024). These cascading ecological impacts reduce ecosystem resilience, limiting the ability of wetlands, drylands, and other ecosystems to recover from repeated climatic disturbances. Consequently, environmental systems are becoming increasingly dynamic, interconnected, and difficult to monitor, understand, and predict (Han et al., 2024).

Although these environmental challenges affect all regions of the world, their intensity and the capacity to respond differ considerably between developed and developing countries(Sezgin et al., 2021). Developed countries generally benefit from advanced environmental monitoring systems, stronger technological infrastructure, and greater financial resources. This enables effective climate observation and early warning. In contrast, many developing countries experience greater vulnerability because of

limited monitoring infrastructure, inadequate financial resources, and weaker institutional capacity. These constraints make it difficult to detect, analyse, and respond to environmental and climatic variability (Berger et al., 2021). Conventional monitoring methods and Indigenous Knowledge Systems (IKS) have both contributed to climate adaptation and environmental management (Phương et al., 2026). However, these often depend on extensive datasets, sophisticated computational resources, and sustained investment. Whereas IKS are increasingly challenged by rapid climatic changes, urbanisation, land-use transformation, and the gradual loss of traditional ecological knowledge. As a result, both approaches face growing limitations in capturing the complexity of modern environmental systems ((IPCC), 2023). This contributes to decline of ecosystem resilience, and altered hydrological processes. These reduce biodiversity, and the degradation of ecosystem services that support both human well-being and ecological sustainability.

Among the ecosystems most affected by climate variability are wetlands and drylands, which represent opposite ends of the hydrological spectrum (Rohde et al., 2024). Wetlands are water-rich ecosystems whose ecological functioning depends on hydrological connectivity. Drylands are water-limited ecosystems where ecological processes are governed by moisture scarcity. Although these ecosystems differ in their physical characteristics and ecological processes, both are highly sensitive to climatic fluctuations (Liu et al., 2025). Small changes in rainfall patterns, temperature, or water distribution can alter ecosystem functioning. Therefore, this makes both wetlands and drylands important indicators of environmental change. Their contrasting hydrological conditions also provide valuable opportunities for understanding how different ecosystems respond to increasing climatic uncertainty (Diouf et al., 2026).

Wetlands and drylands provide essential ecosystem services that support both ecological integrity and human well-being. Wetlands regulate water flow, improve water quality, store carbon, reduce flood risks, and provide habitats for both flora and fauna (Diouf et al., 2026). Drylands support unique biodiversity, sustain livestock and agricultural production, store carbon in soils and vegetation. However, increasing climate variability has reduced the resilience of both ecosystems.

Protecting and monitoring these ecosystems has therefore become a global environmental priority, requiring more accurate and reliable methods for understanding their complex and dynamic responses to climate variability (Lenton et al., 2024). More frequent droughts, floods, changing rainfall patterns, land degradation, biodiversity loss, and declining water resources are disrupting ecological processes. These changes are threatening the ecosystem services upon which communities depend. Although climate variability is a major driver of environmental change, it is not the only factor contributing to the degradation of wetlands and drylands.

The natural ecosystems are currently exposed to extensive human impacts that are exacerbating their vulnerability to climatic factors and hastening their decline (Tefera et al., 2024). Changes in the natural ecosystems brought about by the expansion of agriculture have been leading to the degradation of natural habitats and the depletion of water resources. Urbanisation processes have led to the encroachment of urban settlements onto the natural ecosystems, replacing them with new man-made

systems and disrupting the hydrological cycle (Ding, 2025). The extent of the damage to the ecosystems by mining has been considerable, as this activity entails several hazardous environmental effects, such as the destruction of habitats, soil degradation and water pollution. The pollution caused by various industrial processes and agriculture results in water contamination and loss of biodiversity (Cheng et al., 2026). Irrigation of certain crops requires excessive abstraction of groundwater, which has adverse consequences for the functioning of drylands and wetlands. The introduction of invasive species and deforestation has also had major impacts on the natural ecosystems, reducing the diversity of species and weakening the resilience to disturbance (Rohde et al., 2024).

However, in combination with human activities, the degradation of ecosystems has become a coupled human-environment problem, not a natural one anymore. Human activities alter environmental conditions and changing environmental conditions intensify human activities, establishing a series of interactions and feedbacks that are difficult to foresee and control (Willcock et al., 2023). For example, long-term drought combined with water resources abstraction can aggravate wetland loss, while land use change accompanied with intensive rainfall can exacerbate land degradation. These two interlaced environmental processes reduce the resilience of ecosystems and cause the dysfunction of ecological processes, as well as weaken the ecosystem services that sustain biodiversity and food production, water security, and livelihoods of human beings (Hissan et al., 2024).

Thus, to grasp the potential interactions of this interconnected system requires an environmental monitoring system that has the capacity to observe natural dynamic processes and human-induced changes in time and space (Torresani et al., 2024). Even with considerable improvements in environmental monitoring, future changes in wet-lands and drylands pose one of the most difficult scientific challenges to learning and predicting ecological dynamics. For this reason, monitoring of such systems involves the ongoing collection, integration and interpretation of extensive amounts of environmental data at various spatial and temporal scales (Han et al., 2024). While these technologies have significantly enhanced our capacity to monitor ecosystem change, existing technologies are not sufficient and do not fully capture the complexity, variation and integrations of environmental systems (Ustin & Middleton, 2021).

Remote sensing is the most widely used method for monitoring the condition of ecosystems over large areas (Sutherland et al., 2026). Remote sensing involves looking at the Earth from satellites or from sensors on airborne platforms for information about what is happening at its surface detection of energy that is reflected or emitted from land, water and plants and changing conditions, such as vegetation health, surface water presence and extent, drought, and others. With remote sensing, it is possible to monitor such things as condition of land cover, size of surface water presence, increases or de-creases in vegetation productivity and other features and dynamics with-out having to access each of these locations (Bayerstadler et al., 2021). Remote sensing data are subject to issues of cloud cover and atmospheric influences, sometimes limited image resolution, and the difficulty of observing changes at smaller scales. Satellite imagery primarily provides information about land surface conditions and is less able to identify more subterranean processes such as ground-water changes.

Environmental analysis can be aided by the use of Geographic Information Systems, which are used to store, organise, analyse and visualise environmental spatial data (Lemenkova, 2023). GIS integrates a set of layers of data in relation to the environment in an attempt to identify relationships and trends across the landscape. Environmental information can be derived from a range of sources that differ in scale and accuracy and use different sensors, such as climate records, satellite observations, ecological surveys and ground sensors. Combining these different sources into a trustworthy information system on ecological function remains a major challenge and important interactions between climate, ecology and human factors can be omitted (Nkululeko et al., 2024).

Hydrological and ecological models have become important tools to simulate eco-system processes and to examine potential future scenarios. Water flow, relation of rainfall and runoff, vegetation dynamics and ecosystem changes can all be represented in mathematical equations based on climate data (Cerezo et al., 2022). Modelling is an approach for assessing eco-system response to climate change or human disturbance impacts, although models simulate a simplified version of real ecosystems because natural eco-systems are more complex and contain feedback effects that are not mathematically quantifiable. Minor changes in input data or assumptions in model are capable of producing major variations in model outputs (Holdgate et al., 1980).

The traditional environmental prediction models are mainly based on relations and functions that are predefined in the models. However, the machine learning algorithms in artificial intelligence (AI) learn to recognize complex patterns in data (Masomeke & Chikoore, 2026). Then, based on these patterns, a model can infer future conditions. These approaches have been used for predicting drought, classifying land cover, predicting biodiversity, or assessing climate change impacts. Nonetheless, AI performance highly depends on the quality and quantity of training data. AI-based approaches to prediction can be unreliable when available data sets are spatially biased, temporally discontinuous, or affected by errors in measurements. In addition, many of the current models are essentially complex systems, so it is difficult to explain the model outcomes, which is essential for scientific purposes and decision-making (Hooftman et al., 2021).

Internet of Things (IoT) has potential to enable new ways to monitor conditions as they happen, through networks of sensors (connected devices) that measure temperature, humidity, soil moisture, water level, air quality etc. These sensors can give high-quality local readings and facilitate early warning. But in the remote environments of wetlands and drylands, the infrastructure, energy, communication technology and maintenance needed to implement the IoT at scale can be difficult (Battin et al., 2023). The large number of connected devices will also generate huge volumes of data, requiring efficient data storage, processing and computation speed.

Therefore, these technologies have greatly contributed to environ-mental monitoring and provided important input for ecosystem management. The increasing scale and severity of climate-induced changes and human-induced disturbances imply that environmental monitoring is becoming an increasingly computer-intensive problem (Cohen & Goward, 2004). It is no longer sufficient to gather

environmental data, but also to integrate information from various sources, to analyse complex processes and interactions, to minimize uncertainty and to make reliable predictions in a given time-scale (Clark et al., 2001). This increased need for more computer-intensive environmental monitoring process has aroused an interest in emerging computing methods, such as quantum computing, which is expected to offer new opportunities for addressing complex environmental modelling and optimization problems(Ajagekar & You, 2019).

The increasing complexity of climate variability and ecosystem responses presents some of the environmental monitoring system challenge. Hence, new quantum technologies open avenues to meet some of these challenges through the use of emerging capabilities for optimisation, simulation and sensing (Hua et al., 2025). There is little awareness of how quantum approaches may serve to complement the existing monitoring framework for climate variability in wetland and dryland environments. There is limited systematic review has been conducted of environmental application, technological readiness, practical limitations and potential value added in applying quantum computing to wetland and dryland ecosystem services in the developing world (Sudmeier-Rieux et al., 2021). This systematic review aims to synthesise current knowledge, identify emerging trends, and establish future research directions.

3. Methodology

This research adopted a systematic literature review method based on the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA 2020). This review aims to provide a transparent, structured, and replicable research method to investigate the current developments, opportunities, limitations, and gaps in research, as well as to suggest future research directions for quantum computing applications to detect climate variability in wetland and dryland ecosystems. In view of the interdisciplinary nature of the subject topic, the review aims to synthesise existing evidence from research fields of environmental science, climate monitoring, remote sensing, artificial intelligence and computational modelling, and quantum information science. The research adopted a systematic search method with predefined eligibility criteria for assessing and critically analysing the quality of the included literature, along with thematic synthesis.

3.1 Systematic Review Approach

This study adopted a systematic literature review methodology guided by the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA 2020) framework. The PRISMA approach was selected to ensure transparency, methodological rigor, reproducibility, and a structured synthesis of existing scientific evidence. Given the interdisciplinary nature of quantum computing applications in environmental monitoring, this review integrates research from environmental science, climate science, remote sensing, artificial intelligence, computational modelling, and quantum information science. The systematic review approach was considered appropriate because research on quantum computing and related quantum technologies for climate variability monitoring remains dispersed across multiple

scientific domains. Existing studies often examine individual technological components, such as quantum algorithms, artificial intelligence models, environmental sensors, or Earth observation systems, without providing an integrated understanding of their applicability to complex ecosystems. Therefore, this review aims to synthesise current knowledge, evaluate technological developments, identify research trends, assess limitations, and determine future opportunities for applying quantum technologies in climate variability monitoring of wetland and dryland ecosystems.

A qualitative thematic synthesis approach was applied to analyse the selected studies. The synthesis focused on key themes including quantum computing applications, quantum sensing, environmental data processing, climate modelling, ecosystem monitoring, computational challenges, technological readiness, and potential contributions to improving monitoring capabilities in climate-sensitive ecosystems.

3.2 Search Strategy

A broad systematic search of the literature was undertaken to locate relevant peer-reviewed papers and scientific reports relevant to quantum technologies, monitoring of climate variability and observations on ecosystems. The search process was designed in accordance with the PRISMA 2020 statement in order to achieve consistency across identification, screening, eligibility, and included elements of the process. The literature searches were performed in multidisciplinary scientific literature bases (Google Scholar, Web of Science and Science Direct databases) for which the scope covers a broad range of disciplines including environmental science, computer science, engineering, artificial intelligence, earth observations, remote sensing and quantum computing. Information from additional sources such as reports from acknowledged scientific and technological organisations were included where appropriate to the emerging quantum theories and environmental applications.The search covered publications from 2017 to 2026. This period was selected because quantum computing research has experienced significant development during this period, while environmental monitoring technologies such as artificial intelligence, remote sensing, and advanced modelling approaches have also expanded rapidly. Search terms were developed around four interconnected thematic domains:

1. Quantum technologies ("quantum computing" OR "quantum computer*" OR "quantum algorithm*" OR "quantum machine learning" OR "quantum sensing" OR "quantum optimisation")
2. Climate variability and environmental monitoring ("climate variability" OR "climate change" OR "climate monitoring" OR "environmental monitoring" OR "ecosystem monitoring" OR "climate modelling")
3. Wetland and dryland ecosystems ("wetland*" OR "dryland*" OR "semi-arid ecosystem*" OR "water-limited ecosystem*" OR "terrestrial ecosystem*")
4. Computational and monitoring approaches ("remote sensing" OR "artificial intelligence" OR "machine learning" OR "hydrological modelling" OR "Earth observation" OR "environmental prediction")

Boolean operators "AND" and "OR" were used to combine keywords within and between thematic domains to ensure broad retrieval while maintaining relevance.

3.3 Eligibility Criteria

Studies were included based on predefined criteria to ensure that selected publications were relevant to the objectives of the review.

IC1. Publications written in English

IC2. Peer-reviewed journal articles, conference papers, systematic reviews, or recognised scientific and institutional reports

IC3. Studies published between 2010 and 2026

IC4. Studies examining quantum computing, quantum algorithms, quantum sensing, or quantum-enhanced computational approaches

IC5. Studies addressing climate variability monitoring, environmental modelling, ecosystem observation, remote sensing, or climate prediction

IC6. Studies providing empirical findings, computational frameworks, simulations, theoretical developments, or methodological contributions relevant to environmental applications

IC7. Studies with relevance to wetland, dryland, or climate-sensitive ecosystem monitoring

3.4 Exclusion Criteria

Studies were excluded where they did not meet the objectives of the review.

EC1. Publications unrelated to quantum technologies or environmental monitoring

EC2. Studies focusing exclusively on quantum theory without potential environmental applications

EC3. Studies addressing climate change without relevance to monitoring, modelling, prediction, or computational analysis

EC4. Editorials, opinion papers, abstracts, or publications lacking sufficient methodological information

EC5. Duplicate records identified across databases

EC6. Studies where full-text access was unavailable

3.5 Quality Assessment of Included Studies

Weighted quality assessment was employed to index methodological quality and relevance of included studies. For each publication, a score from 1 to 5 was provided based on criteria, covering scientific relevance, transparency of methods, computational aspects, environmentally relevance, and level of reporting.

Table 1
Criteria Used for the Quality Assessment of Included Studies

Score	Interpretation
1	Low relevance with weak methodological contribution
2	Limited relevance and insufficient methodological detail
3	Moderate relevance with acceptable methodological quality
4	High relevance with strong methodological contribution
5	Highly relevant study with robust methodology and significant contribution

This weighting method made sure that the relatively more rigorous theoretical evidence was sent into the thematic synthesis to a greater degree, and that the correlation between quantum technology and environmental monitoring was more clearly and directly involved.

3.6 PRISMA Flow Diagram and Study Selection

The process of study selection was completed according to the four stages of the PRISMA protocol (Kandathil and Khan, 2000): identification, screening, eligibility, and inclusion. The initial search of the database retrieved [insert number] records from Web of Science, Science Direct, and Google Scholar. After duplicates were identified, the remaining publications were screened for relevance by the title and abstract. For the remaining articles, the publications were further reviewed to confirm the research topics. Articles that did not have a focus on quantum technology applications, climate variability monitoring, ecosystem monitoring, or other computational methods were removed. Articles which remained following screening were further screened according to the eligibility criteria for inclusion in the qualitative data analysis. Articles that did not provide sufficient description of the methods, applications, or observed environmental phenomenon, were then omitted. The remaining publications were then utilized for the qualitative thematic synthesis (Fig. 1).

4. Findings

The findings of this systematic review are presented in a tabular format (Table 1), followed by a narrative synthesis of the key themes identified across the included studies.

4.1 Overview of Included Studies

A total of 17 studies published between 2017 and 2026 were included in the qualitative synthesis. The included studies comprised peer-reviewed journal articles, review papers, simulation studies, experimental investigations and conceptual studies identified through systematic searches of Google Scholar, Web of Science and ScienceDirect in accordance with the PRISMA 2020 framework. The evidence base was internationally distributed, with studies originating from North America, Europe, Asia and multinational collaborations, demonstrating the global nature of research on quantum computing

applications in environmental monitoring. Publication trends indicated a gradual increase in research activity over the review period, reflecting growing scientific interest in applying quantum computing to climate science and environmental monitoring. The reviewed studies investigated diverse quantum computing approaches, including quantum machine learning, quantum optimisation, quantum algorithms, quantum sensing and hybrid quantum–classical computing, applied to climate modelling, climate forecasting, remote sensing, hydrological modelling, environmental monitoring, atmospheric observation and ecosystem management. Collectively, the reviewed literature demonstrates that quantum computing is an emerging computational paradigm with considerable potential for addressing computationally intensive environmental problems while highlighting important technological limitations that currently restrict large-scale practical implementation.

Systematically, the reviewed literature consisted of review studies, simulation studies, experimental investigations and conceptual papers. Review studies synthesised current developments and future opportunities for quantum computing in environmental monitoring, while simulation and experimental studies evaluated the performance of quantum algorithms and quantum machine learning models for solving complex environmental and climate-related problems. Conceptual studies explored the future role of quantum computing in addressing limitations associated with conventional computational methods. Across the reviewed literature, climate modelling emerged as the most frequently investigated application, followed by climate forecasting, environmental data processing, remote sensing, atmospheric monitoring, hydrological modelling and water resource management. Although the reviewed studies consistently demonstrated the considerable potential of quantum computing to improve computational efficiency, predictive modelling and optimisation of environmental systems, they also identified important challenges related to limited quantum hardware, scalability, quantum error correction, high implementation costs and the early technological maturity of existing quantum computing platforms.

Table 1
Summary of findings

Author(s) and year	Region	Quantum method identified	Type of study	Key findings	Main theme
Berger et al. (2021)	Global	Quantum computing; quantum algorithms	Review	Identified climate change as a promising application domain for quantum technologies, particularly for computationally intensive modelling and optimisation problems. The study also highlighted technological maturity, accessibility and scalability as important barriers.	Climate modelling and computational optimisation
Ajagekar and You (2022)	United States / Global	Quantum computing; quantum artificial intelligence	Review and conceptual	Demonstrated the potential of quantum computing and quantum AI to address complex optimisation problems associated with energy systems, sustainability and climate neutrality.	Sustainable resource optimisation
Biamonte et al. (2017)	Global	Quantum machine learning	Review	Established quantum machine learning as an emerging field combining quantum computation with machine-learning approaches, with potential advantages for selected	Quantum machine learning

Author(s) and year	Region	Quantum method identified	Type of study	Key findings	Main theme
				computational problems.	
Arute et al. (2019)	United States	Superconducting quantum computing	Experimental	Demonstrated quantum computational performance on a specialised problem that was impractical for contemporary classical systems, providing evidence of experimentally achievable quantum computational advantage.	Quantum computational advantage
Cerezo et al. (2021)	United States / Global	Variational quantum algorithms	Theoretical and computational study	Demonstrated that barren plateaus can severely affect the optimisation of parametrised quantum circuits, highlighting an important limitation for practical quantum machine-learning applications.	Quantum optimisation and trainability
Cerezo et al. (2022)	Global	Quantum machine learning	Review	Identified major challenges in quantum machine learning, including data encoding, scalability, trainability and establishing meaningful quantum advantage over classical approaches.	QML limitations and opportunities

Author(s) and year	Region	Quantum method identified	Type of study	Key findings	Main theme
Khan and Robles-Kelly (2020)	Australia / Global	Quantum machine learning	Comparative review	Examined quantum and classical machine-learning approaches and emphasised that claims of quantum advantage should be evaluated according to specific computational tasks rather than assumed superiority.	Quantum–classical comparison
Reichstein et al. (2019)	Global	Artificial intelligence / deep learning	Review and perspective	Demonstrated how AI and deep learning can improve Earth-system science by extracting complex relationships from large environmental datasets, providing an important classical baseline for quantum-enhanced approaches.	AI for Earth-system monitoring

Author(s) and year	Region	Quantum method identified	Type of study	Key findings	Main theme
Ustin and Middleton (2021)	United States / Global	Remote sensing; Earth observation	Review	Highlighted the growing importance of Earth observation for ecological monitoring while identifying limitations related to spatial and temporal resolution, data integration and environmental complexity.	Remote sensing and ecosystem monitoring
Rohde et al. (2024)	Global	Earth observation / environmental mapping	Empirical and geospatial modelling	Demonstrated the importance of groundwater-dependent ecosystems in drylands and highlighted the need for improved spatial information to support conservation and environmental management.	Dryland ecosystem monitoring
Moss et al. (2024)	Global	Environmental modelling / climate analysis	Empirical	Showed that drought can act as a major driver of ecological transformation, reinforcing the need for improved monitoring and prediction of climate-driven ecosystem change.	Drought and ecosystem resilience
Page et al. (2021)	Global	PRISMA methodology	Methodological guideline	Established updated reporting standards for systematic	Systematic review methodology

Author(s) and year	Region	Quantum method identified	Type of study	Key findings	Main theme
				reviews, supporting transparent identification, screening, eligibility assessment and synthesis of scientific evidence.	
Feynman (1982)	United States	Quantum computing	Theoretical and conceptual	Proposed the use of quantum computers to simulate quantum physical systems more efficiently, providing a foundational theoretical basis for quantum computation.	Foundations of quantum computing
Farhi et al. (2000)	United States	Adiabatic quantum computation / quantum optimisation	Theoretical	Introduced adiabatic quantum computation as a framework for solving computational problems through controlled quantum evolution, providing foundations for subsequent quantum optimisation methods.	Quantum optimisation
Schuld and Petruccione (2021)	Germany / South Africa / Global	Quantum machine learning	Book synthesis	Provided a comprehensive treatment of machine learning using quantum computers, including quantum data representations, quantum	Quantum machine learning

Author(s) and year	Region	Quantum method identified	Type of study	Key findings	Main theme
				learning algorithms and implementation challenges.	
Fan and Han (2022)	China / Global	Hybrid quantum–classical computing	Review and conceptual	Highlighted hybrid quantum–classical architectures as a practical pathway for exploiting quantum processors while retaining classical computing for large-scale computational workflows.	Hybrid quantum–classical computing
Wang et al. (2021)	Global	Variational quantum algorithms	Computational theoretical	Demonstrated the impact of noise on variational quantum algorithms and showed how hardware noise can produce optimisation difficulties, reinforcing concerns about the NISQ environment.	Quantum noise and scalability

5. Discussion

The 17 studies from Table 1 synthesised in this review, demonstrated an emerging convergence between quantum computing, artificial intelligence and climate-environmental science. Collectively, the studies indicated that quantum approaches are being investigated for climate modelling, machine learning, optimisation, remote sensing, environmental monitoring and complex computational problems. However, the findings also demonstrated that the field remains at an early stage of development. Berger et al. (2021) positioned quantum technologies as an emerging opportunity for climate science, while Biamonte et al. (2017) established quantum machine learning (QML) as a broader computational paradigm capable of combining quantum representations with machine-learning approaches. This emerging potential is reinforced by Ajagekar and You (2022), who identified quantum optimisation and

quantum artificial intelligence as promising approaches for complex sustainability problems. Hence, these studies suggest that the principal contribution of quantum computing to climate variability monitoring is currently its potential to address selected computationally demanding tasks rather than its replacement of conventional environmental-computing systems.

A prominent pattern in the summary table is the growing importance of QML. Biamonte et al. (2017) provided the foundational basis for understanding QML as an intersection between quantum computation and machine learning. Although, Schuld (2018) and Petruccione (2021) demonstrated how quantum learning is formulated through quantum feature representations, variational models and quantum classifiers. Khan and Robles-Kelly (2020) further demonstrated the relevance of quantum learning to machine-learning problems, mainly where quantum representations may offer alternative approaches to feature mapping and classification. In climate applications, this is important because environmental datasets are high-dimensional, nonlinear and heterogeneous. Reichstein et al. (2019) demonstrate the growing importance of artificial intelligence for Earth-system science, particularly for extracting patterns from complex environmental datasets. The quantum literature therefore extends an already established trajectory in environmental artificial intelligence by asking whether selected computational tasks can benefit from quantum representations or quantum processing. Nevertheless, the evidence reviewed here does not establish that QML consistently outperforms classical machine learning. Cerezo et al. (2021) and Cerezo et al. (2022) identify important challenges associated with trainability, barren plateaus and the practical realisation of quantum advantage. Consequently, the environmental relevance of QML should be evaluated through direct comparison with strong classical baselines rather than through theoretical claims of superiority.

The second major pattern concerns optimisation. Ajagekar and You (2022) demonstrated the relevance of quantum optimisation to complex sustainability problems, while Farhi et al. (2000) provided the theoretical foundation for adiabatic quantum computation and optimisation-oriented quantum algorithms. Fan and Han (2022) further highlighted the importance of hybrid quantum-classical computing as a practical direction for contemporary quantum applications. These contributions are particularly relevant to climate variability monitoring because environmental management frequently involves constrained optimisation. Wetland management require decisions concerning water allocation, restoration priorities and competing ecosystem services. Whilst dryland management involves drought response, water-resource allocation, land-use planning and adaptation strategies. The reviewed evidence therefore suggests that quantum optimisation may become relevant where the number of possible environmental decisions creates a computationally difficult search space. However, the theoretical capacity of an optimisation algorithm does not establish practical advantage. Environmental applications must demonstrate that the quantum approach provides measurable improvements over established classical optimisation methods under realistic computational conditions.

The review further identified remote sensing and environmental observation as important application areas. Ustin and Middleton (2021) demonstrated the continuing importance of remote sensing and artificial intelligence for environmental monitoring, while Rohde et al. (2024) illustrated the increasing

role of advanced computational methods in analysing complex Earth-system observations. Within the quantum literature, quantum algorithms and quantum-enhanced learning provide a possible extension of these approaches. This is particularly relevant to wetlands and drylands because satellite observations can provide repeated spatial information on vegetation condition, surface-water dynamics, land cover and environmental change across areas where ground-based monitoring is limited. Quantum-enhanced image analysis could therefore be investigated for classification, feature extraction and anomaly detection. However, Otgonbaatar and Kranzlmüller (2023) caution that quantum advantage in satellite-image processing depends on whether quantum models can actually generalise better than classical approaches and whether the required quantum resources can be justified. This reinforces the conclusion that remote-sensing applications should initially be treated as experimental opportunities rather than established operational solutions.

The findings also highlighted the importance of climate modelling and simulation. Berger et al. (2021) discuss the potential of quantum technologies for climate science, while Schuld and Petruccione (2021) provide the theoretical basis for understanding how quantum machine-learning methods can be incorporated into computational workflows. More recent climate-focused work by Schwabe et al. (2025) identified several possible applications, including solving differential equations, improving parameterisations of Earth-system models, optimisation of model parameters and analysis of climate-model outputs. Their work is relevant because it places quantum computing within existing climate-modelling architectures rather than presenting it as an isolated technology. This supports the hybrid perspective identified by Fan and Han (2022), in which classical and quantum computing can perform complementary functions. Therefore, such an architecture is likely to be more realistic for environmental monitoring because data acquisition, storage, pre-processing and many analytical operations continue to depend on classical computing infrastructure.

The findings also required careful interpretation in relation to the concept of quantum advantage. Arute et al. (2019) provided a landmark experimental demonstration of quantum computational advantage for a specialised computational problem. However, their result does not imply that quantum computers automatically provide an advantage for climate or environmental applications. Cerezo et al. (2021, 2022) demonstrated why quantum models may encounter substantial practical limitations, while Wang et al. (2021) further showed how noise can contribute to barren-plateau behaviour in variational quantum algorithms. These findings are important for climate applications because environmental datasets are large, noisy and often incomplete. A quantum algorithm that performs well under ideal simulation may therefore behave differently on noisy intermediate-scale quantum hardware. The findings consequently supports a cautious interpretation. The current literature demonstrates significant computational potential, but practical quantum advantage in climate variability monitoring remains an empirical question.

The technological limitations identified across the studies are further reinforced by the broader environmental-computing literature. Feynman's foundational argument for quantum simulation established the fundamental motivation for using quantum systems to represent complex physical

processes. Although, Farhi et al. (2000) demonstrated how quantum principles could support alternative computational strategies. However, the progression from theoretical possibility to practical environmental application remains constrained by hardware availability, error rates, quad bit stability, circuit depth and scalability. These constraints explain why hybrid approaches currently appear more realistic than fully quantum environmental-monitoring systems. The reviewed studies therefore point towards a gradual transition in which quantum processors are introduced for specific computational kernels while classical high-performance computing remains the principal infrastructure.

An important gap emerging from the synthesis is the limited representation of African environmental systems. Much of the quantum-climate literature is developed in highly instrumented research environments and focuses on general climate models, computational benchmarks or datasets from regions with extensive observational infrastructure. Yet wetlands and drylands in Zimbabwe and other African countries frequently depend on heterogeneous combinations of satellite observations, meteorological records, hydrological measurements and field observations. The findings of the review therefore cannot simply be transferred to these environments without empirical validation. This gap is particularly important because climate variability in African drylands and wetlands has direct implications for water availability, agricultural productivity, biodiversity and ecosystem resilience. Quantum computing can potentially contribute to these challenges through drought prediction, wetland-change detection, hydrological optimisation, vegetation-stress classification and climate-risk mapping, but these applications require locally grounded validation.

The synthesis of the 17 studies indicates that quantum computing is best understood as an emerging complementary technology for climate variability monitoring. Berger et al. (2021) and Reichstein et al. (2019) established the broader need for advanced computational approaches in climate and Earth-system science. While Biamonte et al. (2017), Schuld and Petruccione (2018, 2021), Khan and Robles-Kelly (2020) and Cerezo et al. (2021, 2022) demonstrate both the promise and limitations of quantum learning. Ajagekar and You (2022), Farhi et al. (2000) and Fan and Han (2022) extend the discussion towards optimisation and hybrid computing, while Arute et al. (2019) provided evidence that quantum computational advantage is experimentally achievable under specialised conditions. Ustin and Middleton (2021), Rohde et al. (2024) and related environmental-computing studies demonstrate the relevance of advanced computational analysis to Earth observation and environmental monitoring. Therefore, these findings indicated that the most credible research pathway is not to replace classical climate-monitoring systems, but to identify specific computational bottlenecks where quantum methods can be rigorously tested. For wetlands and drylands, future research should therefore combine real environmental datasets, hybrid quantum-classical architectures and strong classical benchmarks. This would provide the empirical evidence required to determine whether the potential identified across the reviewed literature can translate into measurable improvements in climate variability monitoring and environmental resilience.

6. Conclusion

The study concluded that quantum computing presents a promising emerging approach for strengthening climate variability monitoring in wetlands and drylands. This is achieved through quantum machine learning, optimisation, quantum algorithms, and hybrid quantum–classical methods. The reviewed evidence indicated the potential for improving the analysis of complex climate datasets, pattern recognition, forecasting, remote sensing, hydrological modelling, and environmental resource management. However, the evidence remains predominantly experimental and conceptual, with practical deployment constrained by limited quantum hardware, noise, qubit instability, error-correction requirements, computational cost, and limited ecological datasets.

7. Recommendations

The study therefore recommends that future research prioritise hybrid quantum–classical architectures that integrate quantum methods with established artificial intelligence, remote sensing, and high-performance computing systems. In Zimbabwe, research institutions should develop pilot studies using local wetland and dryland datasets to evaluate the practical value of quantum approaches under real environmental conditions. Investment in quantum computing skills, accessible simulation platforms, interdisciplinary collaboration, and locally generated climate datasets is also recommended. Therefore, rather than replacing conventional climate-monitoring technologies, quantum computing should initially be investigated as a complementary capability for addressing computationally intensive environmental problems and supporting climate-resilient decision-making.

Declarations

Funding: The authors declare that no funds, grants, or other support were received during the preparation of this manuscript.

Data availability: All data generated or analysed during this study are included in this manuscript.

Clinical trial number: not applicable.

Ethics approval: Not applicable. This study did not involve research on human participants or live vertebrates.

Consent to Publish declaration: not applicable.

Consent to Participate declaration: not applicable.

Competing interests: The authors declare no competing interests.

Author contributions: All authors contributed to the study conception and design, system development, data analysis, and writing of the manuscript. Both authors read and approved the final manuscript.

References

1. Ajagekar A, You F. Quantum computing for energy systems optimization: A review and perspective. Renew Sustain Energy Rev. 2022;155:111493. https://doi.org/10.1016/j.rser.2021.111493.
2. Arute F, Arya K, Babbush R, Bacon D, Bardin JC, Barends R, Biswas R, Boixo S, Brandao FGSL, Buell DA, Burkett B, Chen Y, Chen Z, Chiaro B, Collins R, Courtney W, Dunsworth A, Farhi E, Foxen B, Martinis JM. Quantum supremacy using a programmable superconducting processor. Nature. 2019;574:505–10. https://doi.org/10.1038/s41586-019-1666-5.
3. Biamonte J, Wittek P, Pancotti N, Rebentrost P, Wiebe N, Lloyd S. Quantum machine learning. Nature. 2017;549:195–202. https://doi.org/10.1038/nature23474.
4. Cerezo M, Sone A, Volkoff T, Cincio L, Coles PJ. Cost function dependent barren plateaus in shallow parametrized quantum circuits. Nat Commun. 2021;12:1791. https://doi.org/10.1038/s41467-021-21728-w.
5. Cerezo M, Verdon G, Huang H-Y, Cincio L, Coles PJ. Challenges and opportunities in quantum machine learning. Nat Comput Sci. 2022;2:567–76. https://doi.org/10.1038/s43588-022-00311-3.
6. Feynman RP. Simulating physics with computers. Int J Theor Phys. 1982;21:467–88. https://doi.org/10.1007/BF02650179.
7. Khan SU, Robles-Kelly A. Machine learning with quantum computers: A review. IEEE Access. 2020;8:206267–90. https://doi.org/10.1109/ACCESS.2020.3041719.
8. Miroszewski A, Nalepa J, Le Saux B, Mielczarek J. (2023). Quantum machine learning for remote sensing: Exploring potential and challenges. *arXiv preprint arXiv:2311.07626*. https://doi.org/10.48550/arXiv.2311.07626
9. Nammouchi A, Kassler A, Theocharis A. (2024). Quantum machine learning in climate change and sustainability: A short review. *Proceedings of the AAAI Symposium Series, 2*(1), 107–114. https://doi.org/10.1609/aaaiss.v2i1.27657
10. Page, M. J., McKenzie, J. E., Bossuyt, P. M., Boutron, I., Hoffmann, T. C., Mulrow,C. D., Shamseer, L., Tetzlaff, J. M., Akl, E. A., Brennan, S. E., Chou, R., Glanville,J., Grimshaw, J. M., Hróbjartsson, A., Lalu, M. M., Li, T., Loder, E. W., Mayo-Wilson,E., McDonald, S., … Moher, D. (2021). The PRISMA 2020 statement: An updated guideline for reporting systematic reviews. PLoS Medicine, 18(3), e1003583. https://doi.org/10.1371/journal.pmed.1003583.
11. Pastori L, Grundner A, Eyring V, Schwabe M. Quantum neural networks for cloud cover parameterizations in climate models. Mach Learning: Earth. 2026;2(1):015008. https://doi.org/10.1088/3049-4753/ae4981.
12. Reichstein M, Camps-Valls G, Stevens B, Jung M, Denzler J, Carvalhais N, Prabhat. Deep learning and process understanding for data-driven Earth system science. Nature. 2019;566:195–204. https://doi.org/10.1038/s41586-019-0912-1.
13. Sachdeva K, Sachdeva R, Gupta H. (2023). Quantum computing in image processing. *Recent Developments in Electronics and Communication Systems*. https://doi.org/10.3233/ATDE221232
14. Schuld M, Petruccione F. Quantum ensembles of quantum classifiers. Sci Rep. 2018;8:2772. https://doi.org/10.1038/s41598-018-20403-3.

15. Schwabe M, Pastori L, de Vega I, Gentine P, Iapichino L, Lahtinen V, Leib M, Lorenz JM, Eyring V. Opportunities and challenges of quantum computing for climate modeling. Environ Data Sci. 2025;4:e35. https://doi.org/10.1017/eds.2025.10010.
16. Wang S, Fontana E, Cerezo M, Sharma K, Sone A, Cincio L, Coles PJ. Noise-induced barren plateaus in variational quantum algorithms. Nat Commun. 2021;12:6961. https://doi.org/10.1038/s41467-021-27045-6.

Figures

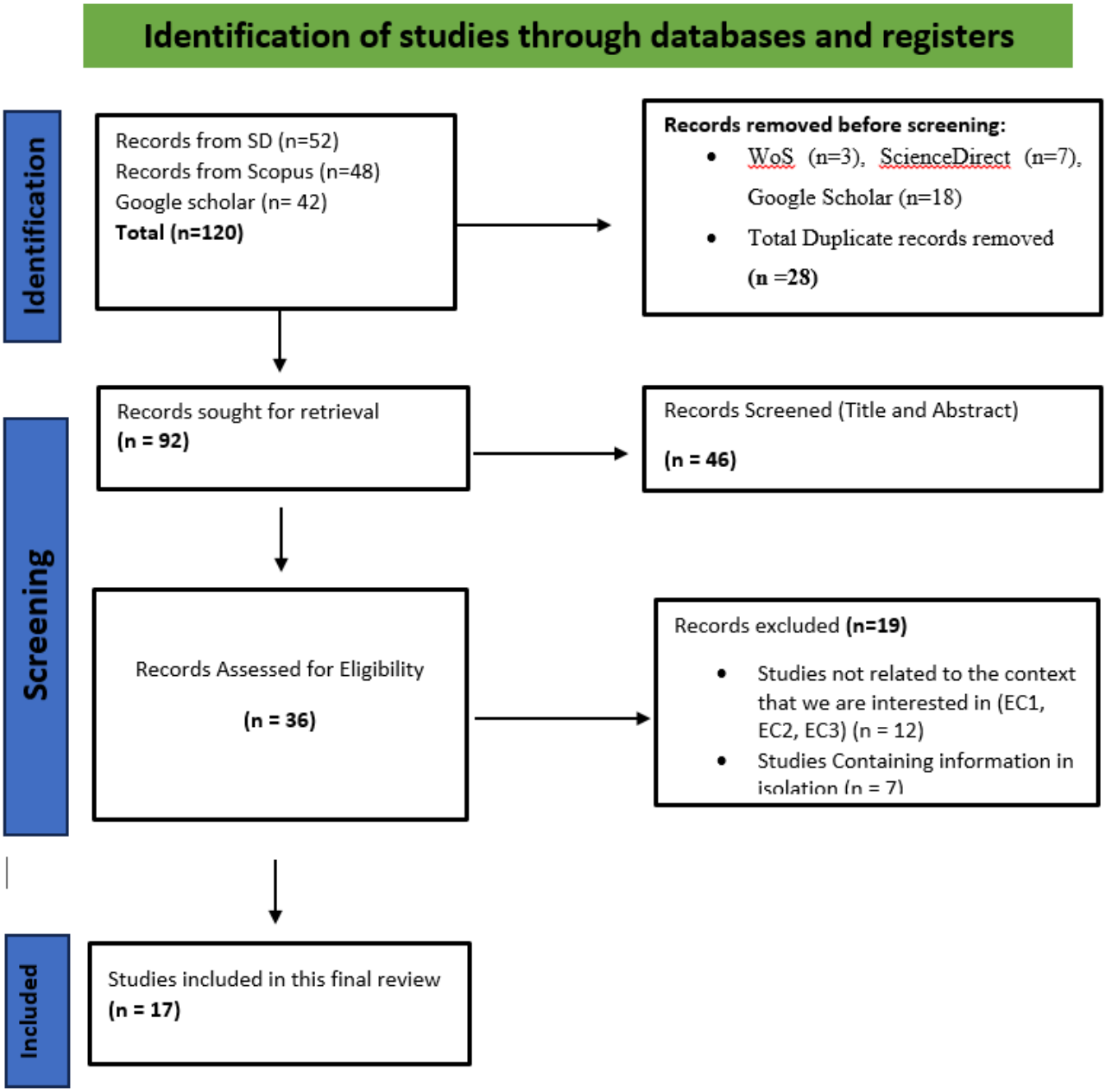


Figure 1

Legend not included with this version.