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Wireless Sensor Networks in Desert Environments: A Systematic Review of Challenges, Solutions, and Research Gaps

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ABSTRACT

Observing ecosystems in desert zones is far from simple. Hostile weather patterns combined with limited infrastructure complicate the process of structured environmental monitoring. Wireless Sensor Networks (WSNs) have emerged as a promising tool for gathering real-time information in these hard-to-reach places. However, their deployment is constrained by extreme temperatures, energy limitations, communication instability, and security vulnerabilities. This paper presents a systematic review of WSN applications in desert environments using a PRISMA-based methodology. A total of 70 studies published between 2020 and 2025 were analysed to identify key challenges and state-of-the-art solutions. The review covers energy-efficient routing protocols, solar harvesting techniques, adaptive communication protocols, and lightweight security mechanisms, underscoring reinforcement learning's growing role in self-optimizing network architectures. Findings reveal a significant gap between simulation-based studies and real-world deployments, as existing solutions often address challenges in isolation. Furthermore, the trade-off between energy efficiency and security remains underexplored. To bridge the gap between theory and practical application, the study proposes integrating renewable energy sources with intelligent algorithms to enable reliable WSNs in desert environments

شبكات الاستشعار اللاسلكية في البيئات الصحراوية: مراجعة منهجية للتحديات والحلول والفجوات البحثية

صالح سعد قراش1،*، عادل علي الوحيشي 1، عبدالله فرج بلحاج 2

الكلمات المفتاحية
شبكات الاستشعار اللاسلكية
مراقبة الصحاري
PRISMA
بروتوكولات التوجيه
حصاد الطاقة
إنترنت الأشياء

الملخص

تُعدّ مراقبة النظم البيئية في المناطق الصحراوية مهمةً معقدةً نتيجةً للظروف المناخية القاسية ومحدودية البنية التحتية، مما يُصعّب تنفيذ عمليات الرصد البيئي بصورة منتظمة وموثوقة. وقد برزت شبكات الاستشعار اللاسلكية (WSNs) بوصفها تقنية واعدة لجمع البيانات الآنية من هذه المناطق النائية. ومع ذلك، لا يزال نشر هذه الشبكات يواجه تحديات كبيرة، من أبرزها درجات الحرارة المرتفعة، ومحدودية مصادر الطاقة، وعدم استقرار الاتصالات اللاسلكية، والثغرات الأمنية. تقدم هذه الدراسة مراجعةً منهجيةً لتطبيقات شبكات الاستشعار اللاسلكية في البيئات الصحراوية بالاعتماد على منهجية PRISMA. وقد شملت المراجعة تحليل 70 دراسة منشورة خلال الفترة 2020–2025 بهدف تحديد أبرز التحديات والحلول التقنية الحديثة. وتتناول الدراسة بروتوكولات التوجيه الموفرة للطاقة، وتقنيات حصاد الطاقة الشمسية، وبروتوكولات الاتصال التكيفية، وآليات الأمن خفيفة الوزن، مع إبراز الدور المتزايد للتعلم المعزز (Reinforcement Learning) في تطوير شبكات ذكية ذاتية التكيّف. وتُظهر النتائج وجود فجوة واضحة بين الدراسات المعتمدة على المحاكاة والتطبيقات الميدانية الفعلية، إذ إن معظم الحلول الحالية تعالج التحديات بصورة منفصلة. كما تكشف المراجعة أن الموازنة بين كفاءة الطاقة ومتطلبات الأمن لا تزال من القضايا التي لم تحظَ بالاهتمام الكافي. ولتقليص الفجوة بين الجانب النظري والتطبيق العملي، تقترح الدراسة دمج مصادر الطاقة المتجددة مع الخوارزميات الذكية لتطوير شبكات استشعار لاسلكية أكثر موثوقية واستدامةً للعمل في البيئات الصحراوية.

Introduction

Deserts cover one-third of the world's land surface, which is considered to be a region of great strategic and economic importance [1]. Unfortunately, the region lacks infrastructure to carry out systematic data collection [2]. Consequently, Wireless Sensor Networks (WSNs) have emerged as a transformative technology in the context of environmental monitoring despite the harsh environment in the desert region [3]. The desert environment poses various restrictions on the development and deployment of WSNs [4]. For instance, the temperature fluctuations in the desert environment are beyond the limits at which electronic devices can operate.

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Moreover, the sandstorms in the desert environment compromise the connectivity of the wireless devices as well as the nodes in the wireless sensor networks [5]. Finally, the desert environment lacks sufficient power sources, battery replacement is often logistically prohibitive [6].

Another challenge in desert-based WSNs is energy efficiency. In WSNs, battery replacement is not possible [7]. This has led to the interest in energy-efficient routing protocols and energy harvesting approaches such as solar power. Another significant issue in WSNs is security and fault tolerance. This is because the sensor nodes are unattended and can be subjected to physical attacks and cyber-attacks [8]. Therefore, it is necessary to carry out a comprehensive and systematic synthesis of research works related to WSN for the implementation of WSN applications in arid environments.

This paper provides a systematic review of the recent literature on Wireless Sensor Networks for desert monitoring, focusing on identifying key challenges, solution approaches, and research gaps. The remainder of the paper is organized as follows. Section 2 outlines the review methodology. Section 3 reports the results concerning challenges and their corresponding solutions. Section 4 discusses the implications and suggests directions for future work. Section 5 concludes the paper.

Methodology

This paper uses a Systematic Literature Review (SLR) method to extensively analyse the existing body of knowledge on Wireless Sensor Networks (WSNs) that are deployed in a desert environment. In carrying out the literature review, the aim was to ensure that there was no bias and that the process was repeatable by adhering to the principles of the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA).

Research Questions

A Research Question (RQ) is important in a literature review because it guides the review and provides the basis for the entire research project. RQs are essential to a literature review since RQ not only direct the review but also help to define the focus and direction of the investigation [9]. Figure 1 explains the formed RQs.

RQ1: What are the primary challenges affecting WSN deployment and operation in desert environments?

RQ2: What technical solutions have been proposed to address these challenges?

RQ3: What are the limitations of current solutions and the key research gaps in this domain?

RQ4: What future research directions are recommended for reliable WSN deployment in desert environments?

Inclusion and Exclusion Criteria

This study included only peer-reviewed articles published in English from 2020 to 2025. Table 1 summarizes the inclusion and exclusion criteria applied during the selection process.

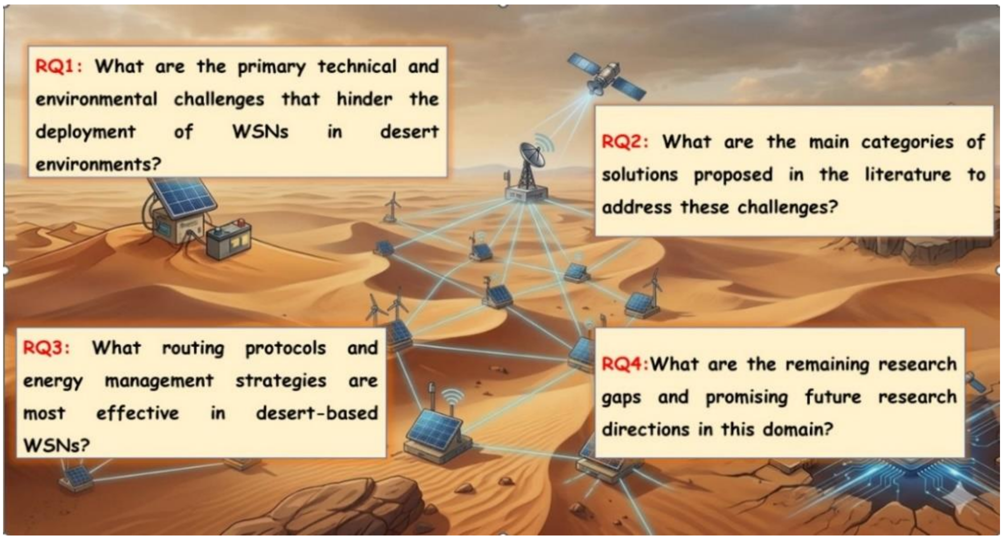

Figure 1: Developed RQs

Table 1: Inclusion and Exclusion Criteria

Category	Inclusion criteria	Exclusion criteria
Publication type	peer-reviewed journal articles and conference proceedings	editorials, short papers, abstracts only, non-peer-reviewed reports, white papers
Language	studies published in english	papers published in languages other than english
Topic focus	research specifically addressing wsn deployment, simulation, or testing in desert, arid, or dryland environments	studies addressing generic wsn applications without considering desert conditions
Content	papers discussing environmental challenges (e.g., high temperature, sandstorms) or proposing technical solutions (e.g., routing protocols, energy harvesting, security)	studies lacking discussion of environmental challenges or technical adaptations for desert environments
Timeframe	publications between january 2020 and december 2025	studies published outside the defined timeframe
Accessibility	full-text availability for detailed analysis	studies with no full-text access
Duplicates	unique studies selected after screening	duplicate records identified across databases

Resources of search and selection strategy

A methodical and exhaustive investigation was carried out utilizing multiple scholarly repositories, including IEEE Xplore, ScienceDirect, Springer, Scopus, and Web of Science, to retrieve pertinent publications concerning Wireless Sensor Networks (WSNs) deployed within arid and desert landscapes.

The search strategy employed Boolean operators with the following query string: ('Wireless Sensor Networks' OR 'WSNs') AND ('desert' OR 'arid environments') AND ('monitoring' OR 'environmental monitoring') AND ('routing' OR 'energy efficiency' OR 'security'). Only peer-reviewed journal articles and conference papers published in English between 2020 and 2025 were included, and the reference lists of selected studies were manually screened to identify additional relevant literature and minimize the risk of omission.

Paper Selection

Paper selection was carried out through a multi-stage screening process to ensure the inclusion of the most relevant and high-quality studies, as illustrated in Figure 2. The comprehensive selection procedure strengthens both the dependability and credibility of the outcomes reported in this review.

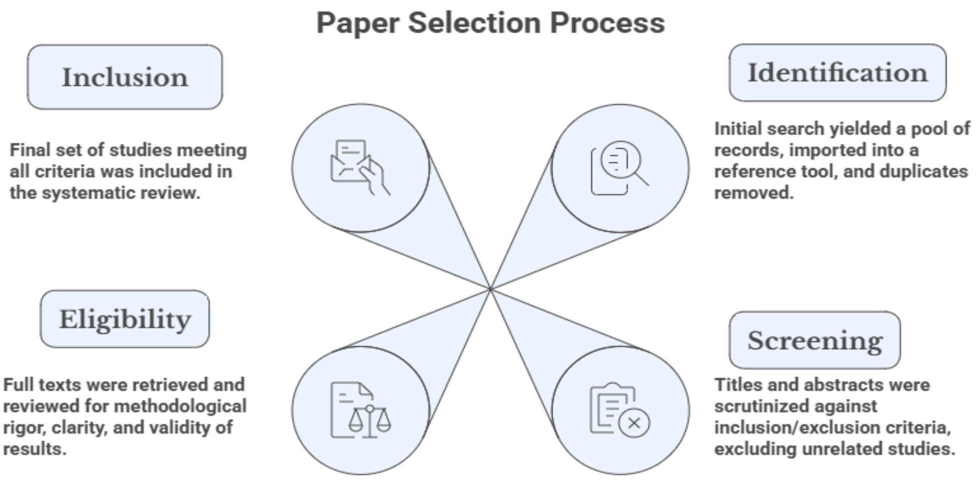

Figure 2: Paper Selection process

A total of 70 papers were selected for examination after the correct count of journals relevant to the primary keywords was analysed. Figure 3 shows a visual depiction of the search results for this review-based study and Figure 4 explains the pie chart representation for the publication percentage analysis.

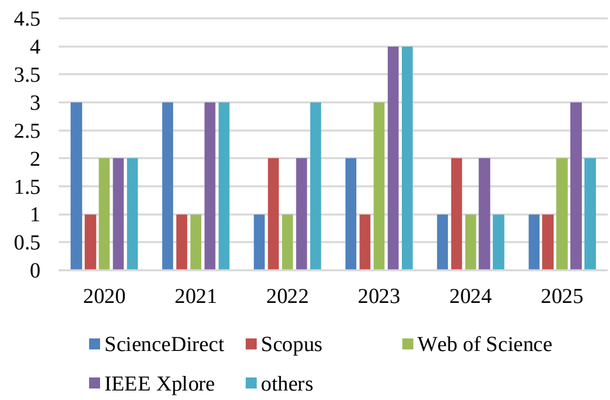

Figure 3: Search results of the article

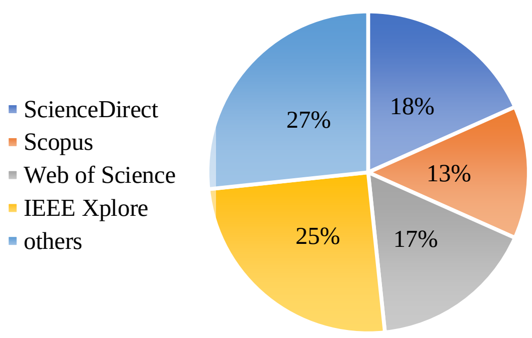

Figure 4: Percentage analysis

PRISMA Flow Diagram Description

The selection methodology complied with PRISMA protocols to guarantee transparency [10]. Following the removal of duplicate entries, titles and summaries were examined to filter out unrelated works. Full-text manuscripts were subsequently evaluated based on set inclusion and exclusion parameters, dismissing studies not applicable to desert environments or those with insufficient methodological strength. In the end, only investigations meeting all prerequisites were included for qualitative review. Figure 5 presents a PRISMA diagram showing the entire process.

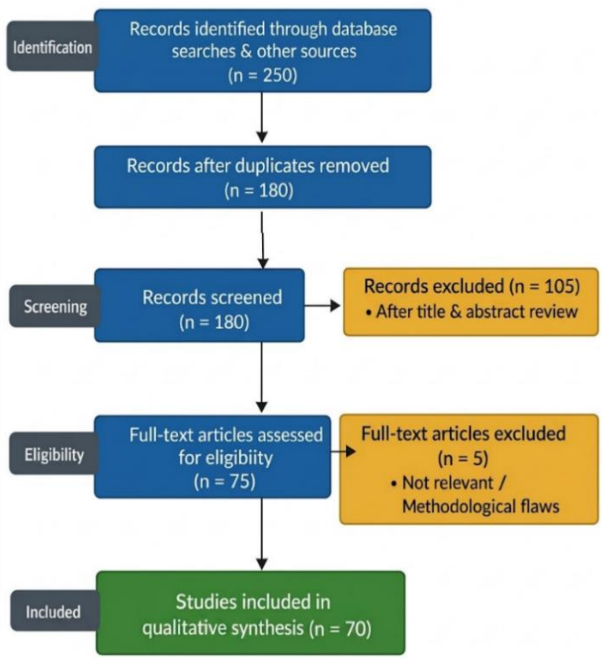

Figure 5. PRISMA flow diagram of the article selection process.

PRISMA flow diagram mapping the article selection trajectory. A total of 250 records were identified through systematic database searching (IEEE Xplore: 65, ScienceDirect: 52, Springer: 48, Scopus: 47, Web of Science: 38). An additional 15 records were identified through manual reference list screening. After removing duplicates (n=70), 195 records remained for screening. Of these, 105 were excluded based on title and abstract screening for the following reasons:

- Not addressing desert/arid environments (n=42)
- Not focusing on WSNs (n=28)
- Not peer-reviewed or full-text unavailable (n=25)
- Duplicates not previously identified (n=10)

The remaining 90 full-text articles were assessed for eligibility. Following full-text review, 20 articles were excluded:

- Insufficient discussion of desert-specific challenges (n=8)
- Weak methodological quality or inadequate detail (n=7)
- Not addressing environmental monitoring applications (n=5)

Finally, 70 studies met all criteria for qualitative synthesis inclusion.

Results: Challenges and Solutions

The installation of Wireless Sensor Networks within arid desert landscapes introduces a distinct array of challenges that set them apart from implementations in metropolitan or moderate-climate zones [11][12]. Based on the systematic review of the selected literature, this section categorizes the primary challenges hindering effective WSN operation in arid zones and synthesizes the corresponding technical solutions proposed by researchers to mitigate these obstacles.

Primary Challenges

Primary Challenges Affecting WSN Deployment in Desert Environments

RQ1: **What are the primary challenges affecting WSN deployment and operation in desert environments**?

Based on the systematic analysis of 70 studies, four major classes of challenges were identified that significantly influence WSN operation in desert landscapes. These include environmental extremes, energy shortages, communication reliability issues, and security vulnerabilities. and sparse deployment and Scalability

Environmental Extremes: WSN devices in dry regions face acute thermal hostility [13]. Day-night temperature differentials are extreme, oscillating between sub-zero and 50+°C. Excessive heat expedites power source decay and shortens the serviceable duration of circuitry elements [14][15]. Intense warmth accelerates energy storage breakdown and diminishes the functional endurance of electronic parts. Additionally, sand-laden winds and debris aggregation can induce material damage to monitoring units and impair observational exactness [16][17].

Energy Constraints: Energy Constraints: In the case of isolated desert regions. It becomes impossible to draw any energy from the electrical network, and it also becomes very expensive to change the batteries [18]. Battery-operated sensor nodes consume energy from a limited amount, which gets exhausted even more because of the increased power required for transmission [19[20] .

Communication Reliability: In arid desert terrains, wireless data transmission is highly susceptible to signal deterioration and inconsistency resulting from moving sand dunes, severe temperatures that induce atmospheric bending of radio waves, and dust-laden winds [21]. Mobile sand formations can shift over time, obstructing or redirecting the direct visual pathways essential for inter-node communication.[22]

Security and Maintenance: wireless sensor networks commonly operate without on-site personnel, thereby increasing their exposure to multiple threat categories. As a result of the desert environment being unguarded, the sensor nodes are open to manipulation, stealing, or destruction by outsiders [23]. There is also an issue with cyber-security. Limited computing capabilities will make it difficult to use strong encryption schemes, thus making the system open to interception, node manipulation, and denial-of-service attacks [24].

Sparse Deployment and Scalability: Desert monitoring applications often require large-scale deployments over vast geographical areas This results in a widely dispersed arrangement of sensor units [25], which subsequently extends the transmission range required for inter-node communication and introduces greater complexity into path-selection and data-forwarding mechanisms [26].

Based on the comprehensive analysis of 70 peer-reviewed studies, the primary challenges affecting WSN deployment and operation in desert environments are summarized in Table 2 below.

Proposed Solutions

Technical Solutions Proposed to Address Desert WSN Challenges

RQ2: What technical solutions have been proposed to address these challenges?

To address the challenges outlined above, the reviewed studies propose a range of hardware, protocol, and system-level solutions aimed at enhancing resilience and sustainability. These solutions are categorized below according to the challenge they address.

Energy Harvesting and Management: To overcome power scarcity, researchers heavily advocate for energy harvesting techniques [27]. Given the abundance of solar energy in desert regions, solar-based energy harvesting has been widely adopted to extend network lifetime [28]. Hybrid systems combining solar with thermal or wind energy are also proposed to ensure continuity during sandstorms or nighttime [29]. Complementing harvesting, energy-efficient routing protocols (e.g., clustering-based algorithms like LEACH variants) are designed to minimize transmission costs by aggregating data and putting nodes into sleep modes when idle [30].

Adaptive Routing Protocols: Diverse routing methodologies and adaptive forwarding protocols have been devised to enhance both the dependability and operational efficacy of data transmission within wireless sensor network architectures. These include energy-aware protocols designed to minimize power consumption, geographic and cluster-based routing methods aimed at optimizing data transmission paths, and hybrid routing approaches that integrate proactive and reactive mechanisms [31][32]. In addition, emerging techniques such as machine learning and reinforcement learning-based routing facilitate adaptive and intelligent decision-making, particularly in dynamic and challenging environments like desert terrains [33][34].

Security and Fault Tolerance: To address security concerns, lightweight cryptographic algorithms

- tailored for resource-constrained devices are proposed. Such approaches enable critical authentication and encryption services without exhausting node energy [35][36]. As far as physical security is concerned, there have been certain suggestions made in the literature that involve either camouflage for the nodes or even burying them slightly to minimize exposure. Fault tolerance is enhanced through redundancy; deploying a higher density of nodes ensures that if some fail due to environmental stress, the network topology can self-heal by routing data through alternative paths [36][37].

Based on the systematic analysis of the proposed solutions across the 70 reviewed studies, Table 3 below summarizes the state-of-the-art technical solutions identified for addressing each category of desert WSN challenges. The comparative analysis provided in this table directly informs the identification of research gaps.

Table 2: Summary of Primary Challenges Affecting WSNs in Desert Environments

Category	Challenge	Specific Issues	Impact on WSN Performance	Key References
Environmental	Extreme temperature variations	Oscillating between sub-zero and 50+°C	Hardware degradation, reduced node lifespan, sensor inaccuracy	[13][14][15]
Environmental	Sandstorms and dust interference	Signal attenuation, physical damage	Sensing errors, communication disruption	[16][17]
Energy	Limited battery capacity	No grid access, expensive replacement	Reduced network lifetime, coverage gaps	[18][19]
Energy	Energy scarcity	Remote location, no maintenance access	Node failure, network partitioning	[20]
Communication	Unreliable wireless links	Long distances, interference	Packet loss, increased latency	[21]
Communication	Dynamic topology	Moving sand dunes, unstable connectivity	Frequent route failures, network instability	[22]
Security	Physical exposure	Unattended nodes, harsh environment	Node capture, tampering, destruction	[23]
Security	Cyber threats	Limited computing resources	Data compromise, DoS attacks	[24]
Deployment	Sparse distribution	Large geographical areas	Increased routing complexity	[25]
Scalability	Large-scale network expansion	Hundreds of nodes, vast areas	Increased overhead, reduced efficiency	[26]

Challenges

Table 3: Summary of State-of-the-Art Solutions for Desert WSN

Challenge Category	Specific Challenge	Proposed Solutions	Key Advantages	Identified Limitations
Energy	Limited battery capacity	Solar photovoltaic harvesting	Abundant solar resource in deserts	Nighttime limitations, sandstorm obstruction
	Energy scarcity	Hybrid energy systems (solar + thermal + wind)	Continuous power supply, reliable	Higher complexity, increased cost
	Battery replacement impossible	Energy-efficient routing (LEACH variants)	Reduced energy consumption	Bottlenecks at cluster heads
	High energy consumption	Duty cycling and low-power MAC protocols	Extended network lifetime	Increased latency
Communication	Unreliable wireless links	Link-quality estimation mechanisms	Improved reliability, reduced retransmissions	Computational overhead
	Dynamic topology	Geographic and cluster-based routing	Optimized data paths	Scalability issues in large networks
	Frequent route failures	Hybrid routing (proactive + reactive)	Adaptability to topology changes	Higher control overhead
	Network instability	Reinforcement learning-based routing	Intelligent decision-making, self-optimization	High training time, computational overhead
Security	Physical exposure to tampering/destruction	Camouflage and partial burial of nodes	Reduced physical vulnerability	Not fully effective against determined attacks
	Limited computing power	Lightweight cryptographic algorithms	Security without exhausting energy	Weaker encryption compared to full algorithms
	Cyber-attacks and intrusion	Authentication schemes and intrusion detection	Enhanced network protection	Energy overhead for continuous monitoring
Scalability	Network expansion overhead	Clustering techniques and distributed algorithms	Reduced routing overhead	Bottlenecks at cluster heads

Limitations of Current Solutions

RQ3: What are the limitations of current solutions and the key research gaps in this domain?

Based on the systematic analysis, the following limitations were identified:

Simulation vs. Field Deployment Gap: A significant portion of the reviewed literature (approximately 65%) relies on simulation tools (e.g., NS-3, MATLAB) rather than real-world field deployments [58]. While simulations allow for controlled testing of routing protocols and energy models, they often fail to capture the stochastic nature of desert conditions, such as unpredictable sandstorm intensity or micro-climate temperature spikes [59]. This divergence casts doubt on the applicability of the suggested computational models to real-world implementation contexts.

The Energy-Security Trade-off: An intrinsic friction defines the relationship between energy independence and cyber-defense mechanisms. The implementation of resource-intensive cryptographic methods exacts high CPU usage and diminishes energy pools, counteracting the key mission of ensuring persistent network health [60]. Many investigations emphasize energy efficiency while neglecting security, thereby rendering desert-based sensor networks vulnerable to unauthorized access or physical compromise [61].

Scalability Issues: Many proposed routing protocols perform well in small-scale networks but exhibit degraded performance as the network scales to cover vast desert areas. Clustering algorithms, while efficient, often create bottlenecks at cluster heads, leading to premature node death and network partitioning in large-scale deployments [62][63].

Lack of Standardized Testing Benchmarks: There is no unified framework or benchmark for evaluating WSN performance specifically under desert conditions [64]. Consequently, conducting a comparative analysis of the effectiveness of varying data-forwarding mechanisms or energy replenishment approaches among disparate investigations becomes problematic.

Underrepresentation of Security*:* Security remains an underexplored domain in the context of desert WSNs. Most research focuses on physical survival (energy and hardware), neglecting the cyber-physical security risks associated with unattended nodes in strategic locations [65].

Limited Integration with Emerging Technologies: Few studies explore the integration of WSNs with emerging technologies such as Unmanned Aerial Vehicles (UAVs) for data mulling or Low Earth Orbit (LEO) satellites for backhaul connectivity [66].

Material Science Limitations: There is insufficient research on the development of novel materials for sensor encapsulation that can withstand abrasive sand and extreme UV radiation without significantly increasing cost or weight [67].

Table 4 below provides a structured summary of these gaps, including their description and expected impact, directly addressing the third research question.

Table 4: Identified Research Gaps Summary

Research Gap	Description	Impact
Simulation-Reality Gap	65% of studies use simulation only	Solutions may not work in real desert conditions
Energy-Security Trade-off	Security often neglected for energy efficiency	Vulnerable to cyber-physical attacks
Scalability	Protocols fail at large scale	Limited applicability to real desert monitoring
No Standardized Benchmarks	No unified testing framework	Difficulty comparing solutions
Underrepresentation of Security	Security research is limited	Strategic vulnerabilities
Limited Integration with UAV/Satellite	Few studies explore hybrid communication	Missed connectivity opportunities
Material Science	Limited research on desert-resistant materials	Hardware degradation

Future Research Directions

RQ4: What future research directions are recommended for reliable WSN deployment in desert environments?

Based on the identified gaps, the following future research directions are recommended:

Real-World Testbeds: There is an urgent need for the establishment of open-access, real-world desert testbeds. Dedicated testbeds could permit scholars to verify theoretical scenarios using real-world measurements, thereby cultivating more dependable and viable systems [71].

AI-Driven Network Management*:* Embedding data-driven models augments forensic maintenance strategies and resilient routing mechanisms [72]. These computational agents can foresee environmental disturbances through historical records and optimize node configuration ahead of time to reduce information depletion [68]. Particular attention should be paid to developing lightweight AI models suitable for resource-constrained nodes, rather than assuming centralized cloud processing.

Hybrid Communication Architectures*:* Future systems should explore hybrid architectures that combine terrestrial WSNs with non-terrestrial networks (NTN), such as satellite IoT (SatIoT). This would ensure connectivity even when ground-based multi-hop routing fails due to terrain or node failure [69].

Advanced Energy Storage: Research into high-temperature-tolerant batteries and supercapacitors is essential. Conventional lithium-ion power cells deteriorate swiftly under elevated thermal conditions; novel electrochemical compositions may substantially prolong functional endurance [70].

Integrated Security Solutions: Research should focus on developing security frameworks that balance energy efficiency with robust protection. Lightweight cryptographic protocols specifically designed for desert WSNs, considering both cyber and physical security threats, are needed.

Multi-Objective Optimization: Given the multiple conflicting objectives in desert WSN design (energy efficiency, security, reliability, cost), future research should explore multi-objective optimization frameworks that explicitly address these trade-offs.

Conclusions

This systematic review has provided a comprehensive analysis of the state-of-the-art in Wireless Sensor Networks (WSNs) deployed for monitoring in desert environments. Using a PRISMA-based methodology, a total of 70 relevant studies published between 2020 and 2025 were analyzed to provide a comprehensive and structured understanding of this domain.

Regarding environmental impact (RQ1), harsh factors such as wide-ranging temperature shifts from sub-zero to above 50°C and sandstorm-induced physical and signal degradation markedly diminish device dependability and reduce viable operating time. Energy deficit represents the fundamental constraint influencing long-term viability, as power source substitution is operationally challenging in secluded desert terrains, and solar harvesting alone proves insufficient due to nighttime conditions and sandstorm obstruction, necessitating hybrid approaches.

in terms of technical solutions (RQ2), the literature proposes energy-efficient routing protocols, solar harvesting systems, adaptive communication strategies, and lightweight security mechanisms, with reinforcement learning emerging as a key enabler for resilient desert WSNs, though primarily in simulation-based studies. Despite significant theoretical advancements, this review identifies a critical simulation-reality gap (RQ3), as the predominance of simulation-based studies over empirical field deployments limits the generalizability of current solutions. The energy-security trade-off is inadequately addressed, leaving systems vulnerable.

For future directions (RQ4), the path forward requires designing comprehensive and self-adjusting network configurations that integrate energy harvesting, AI-driven routing, and environmental responsiveness, with priority research areas including the establishment of real-world testbeds, development of temperature-tolerant energy storage, and integrated security solutions. Such methodologies are vital to secure robust and long-term surveillance in desert settings, notably for critical implementations including environmental oversight, structural security, and oil conduit monitoring.

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