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Enabling Sustainability Through the Internet of Things: A Narrative Review of Global Applications and Challenges

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ABSTRACT: The Internet of Things (IoT) has emerged as a transformative framework with broad applications in healthcare, agriculture, energy, and urban systems. This review aims to synthesize current evidence on IoT adoption, assessing both its benefits and the challenges hindering large-scale implementation. Literature was systematically retrieved from major databases, including Scopus, Web of Science, PubMed, and Google Scholar, using targeted keywords and strict inclusion and exclusion criteria. Findings reveal consistent evidence of IoT's contribution to efficiency and sustainability: precision agriculture improves yields and resource use, while smart energy systems reduce consumption in urban infrastructures. Comparative results demonstrate disparities between developed and developing countries, with advanced economies emphasizing integrated high-tech solutions and resource-limited settings prioritizing affordable, accessible innovations. The discussion highlights the critical role of systemic and policy factors, including regulatory support, infrastructural investment, and societal trust, in shaping adoption outcomes. Emerging technologies such as blockchain and machine learning show promise for addressing challenges of security and energy efficiency but require further empirical validation in real-world contexts. While current research supports IoT's role in advancing sustainable development, significant gaps remain in understanding its long-term socio-economic impacts and scalability. The findings emphasize the urgency of policy interventions, inclusive strategies, and interdisciplinary research to fully realize IoT's potential as a driver of sustainable and equitable global transformation.

Keywords: Internet of Things, Smart Cities, Energy Efficiency, Precision Agriculture, Iot Security, Blockchain Applications, Sustainable Development.

INTRODUCTION

The Internet of Things (IoT) has emerged as one of the most transformative paradigms of the 21st century, reshaping human interaction with environments, industries, and societies. Over the past decade, IoT deployments across sectors such as healthcare, agriculture, transportation, and energy have demonstrated how interconnected systems can drive efficiency, enhance decision-making, and promote sustainability. This impact is visible through the growth of smart cities, digital health systems, and intelligent transportation—all built upon sensors, communication protocols, and analytics platforms (Figueroa-Lorenzo et al., 2019; Alshudukhi, 2025).

However, these advancements bring with them complex challenges related to data security, energy consumption, and systems integration. Data management and security are now central concerns, with blockchain-based approaches increasingly explored for their potential to enhance transparency and privacy, especially in sensitive domains like healthcare (Figueroa-Lorenzo et al., 2019; Alshudukhi, 2025). Simultaneously, IoT serves as a core enabler of sustainability in urban infrastructures by driving improvements in waste management, environmental monitoring, and mobility systems. Yet, issues of scalability and interoperability demand further exploration, requiring cross-sectoral reviews that bridge technical and policy lenses.

Empirical data affirm IoT's environmental benefits: IoT-based energy management has reduced emissions in industrial and urban systems (Pushpavalli et al., 2024; Rodrigues et al., 2022), and precision agriculture has advanced productivity while conserving resources. Smart waste systems also contribute to improved recycling and resource recovery. Nevertheless, these gains are tempered by the energy demands of IoT infrastructure itself—particularly data centers and cloud platforms (Conti et al., 2022; Mahadik et al., 2025). Thus, IoT represents both a solution and a contributor to sustainability challenges.

Regionally, IoT has proven useful in addressing issues such as water resource management. LPWAN-supported monitoring systems enable real-time data collection for water distribution, crucial in regions affected by scarcity (Cheng et al., 2024; Staude et al., 2024). These case studies illustrate the importance of tailoring IoT implementation to specific geographic and socio-economic contexts.

Recent advances in machine learning and AI enhance IoT's utility through predictive analytics and autonomous decision-making. Applications range from preventive health monitoring to traffic optimization. However, their deployment introduces further concerns around ethics, privacy, and algorithmic bias.

Security remains a core barrier to broader IoT adoption. Weak encryption and fragmented security protocols render systems vulnerable (Szymoniak et al., 2025). Solutions such as lightweight cryptography and decentralized architectures are essential for resilience. Energy efficiency also presents a key challenge. While microbial fuel cells and adaptive energy harvesting show promise, their large-scale application is not yet realized (Erofeeva, 2025).

Interoperability issues emerge especially in industrial systems using varied protocols and proprietary hardware. Standardization of frameworks is vital to enable smooth system integration (Zhao et al., 2024). Additionally, socio-economic impacts remain underexplored, including issues of digital access and equity (Alshudukhi, 2025; Erofeeva, 2025).

This review aims to provide a global synthesis of IoT applications with emphasis on security, energy, and integration. It evaluates technological advances, adoption barriers, and policy considerations to offer a holistic understanding of IoT's role in sustainable development.

METHOD

The methodology of this review was designed to ensure a rigorous, systematic, and transparent process in identifying, selecting, and analyzing the relevant literature on the Internet of Things (IoT) and its applications across different sectors. Given the interdisciplinary nature of IoT research, which spans fields such as computer science, engineering, healthcare, environmental science, and social sciences, multiple strategies were employed to capture the breadth and depth of current knowledge. This section describes in detail the databases consulted, the search strategy including keywords and Boolean operators, the inclusion and exclusion criteria applied, the types of studies considered, and the screening and evaluation process.

The first step in conducting this review involved identifying appropriate databases that provide access to high-quality, peer-reviewed literature. Four primary databases were selected to ensure coverage of multidisciplinary sources. Scopus was chosen for its extensive indexing of peer-reviewed journals, conference proceedings, and its analytical tools for citation tracking and research mapping. Web of Science was also selected because of its comprehensive coverage of high-impact journals and its structured indexing, which enables researchers to assess research trends and networks in the IoT domain. Google Scholar was included to broaden the search scope and capture additional grey literature, such as conference papers or institutional reports, which may not always appear in the more selective databases but nonetheless contribute valuable insights. Finally, PubMed was incorporated specifically to identify literature on IoT applications in healthcare, recognizing its specialization in medical and biomedical research (Figueroa-Lorenzo et al., 2019). By using these four databases, the review aimed to strike a balance between depth and breadth, ensuring both comprehensiveness and relevance.

The search strategy was carefully developed to maximize both sensitivity and specificity. A series of keywords was defined to capture the broad spectrum of IoT applications. These included: "Internet of Things" (IoT), "smart agriculture," "healthcare IoT," "energy management IoT," "IoT security," "blockchain in IoT," and "machine learning IoT applications." These terms were chosen because they reflect both the core concept of IoT and its key domains of application. Boolean operators (AND, OR) were applied to refine the search queries. For example, queries such as "IoT AND agriculture AND sustainability" or "healthcare AND IoT AND data security" were used to focus the search on specific areas. This strategy allowed for the inclusion of studies that addressed the intersections of IoT with important themes such as sustainability, data security, and artificial intelligence.

In establishing inclusion and exclusion criteria, this review applied several filters to ensure that only the most relevant and reliable studies were analyzed. Articles were required to be peer-reviewed to guarantee academic rigor and reliability. Both systematic reviews and case studies were considered, as well as empirical research articles, to capture theoretical, methodological, and practical perspectives. Conference proceedings and white papers were also included when they contributed novel or significant insights, particularly in areas where the literature remains emergent. In terms of publication years, the focus was on studies published within the past five years, ensuring that the review concentrated on the most recent developments in IoT research. However, older studies were not automatically excluded if they provided foundational theories or frameworks critical to understanding the evolution of IoT applications. This flexibility ensured that the review maintained both contemporaneity and historical grounding.

Language was also an important inclusion factor. Studies published in English were prioritized given its status as the lingua franca of scientific communication. Nevertheless, studies in other languages were considered if they provided unique insights into IoT applications, particularly in regions where English is not the dominant academic language but where IoT adoption has had significant impacts. This approach acknowledged the global nature of IoT research and the need to capture diverse perspectives. Geographic context was another critical consideration. Articles from both high-income and low- to middle-income countries were included to ensure a comprehensive understanding of how IoT is being applied in different socio-economic settings. Particular attention was given to studies from resource-constrained environments, where IoT technologies often offer transformative potential in addressing challenges such as healthcare access, agricultural productivity, and water management (Cheng et al., 2024; Staude et al., 2024).

The subject relevance criterion was equally significant. Only studies that directly addressed IoT applications in sectors such as healthcare, agriculture, energy, or security were included. This focus ensured that the review did not diverge into tangential topics and maintained coherence in addressing the stated research objectives. Additionally, studies had to discuss challenges or barriers to IoT adoption, as this review aimed to highlight both opportunities and constraints. For instance, articles that examined the security vulnerabilities of IoT devices, the energy consumption of IoT-enabled infrastructures, or the interoperability challenges between different systems were deemed particularly valuable (Szymoniak et al., 2025; Zhao et al., 2024).

The selection of studies followed a multi-stage process. After the initial search results were retrieved, titles and abstracts were screened to assess their relevance. Articles that did not directly pertain to IoT applications were excluded at this stage. For those that appeared relevant, full-text versions were obtained and thoroughly reviewed. This stage involved evaluating the methodological quality, scope of analysis, and alignment with the review's objectives. Duplicate entries across databases were identified and removed to avoid redundancy. The final pool of studies was then organized thematically, based on their focus on specific IoT applications or challenges, such as healthcare, energy management, or security.

To ensure reliability, the evaluation of studies considered both the methodological rigor and the relevance of the findings. Studies were assessed for the robustness of their data collection methods, the appropriateness of their analytical frameworks, and the clarity of their conclusions. Articles that lacked sufficient methodological detail or that drew overly speculative conclusions without empirical support were excluded. This ensured that the body of literature analyzed was not only comprehensive but also credible and of high academic quality.

Through this methodology, the review sought to construct a balanced and holistic understanding of the state of IoT research. By combining rigorous database searches, carefully chosen keywords, strict inclusion and exclusion criteria, and a transparent selection process, the methodology ensured that the literature reviewed addressed the central themes of IoT security, energy efficiency, integration, and application across diverse socio-economic and geographic contexts. Ultimately, this methodological approach aimed to produce findings that are not only academically robust but also practically relevant, contributing meaningful insights to both scholars and practitioners working in the rapidly evolving domain of IoT.

RESULT AND DISCUSSION

The findings of this narrative review are presented thematically to capture the breadth of current knowledge on the Internet of Things (IoT) and its diverse applications. The results highlight empirical evidence supporting IoT adoption, factors influencing outcomes across sectors, and comparative insights across geographic regions. In analyzing these themes, the review underscores both the opportunities and challenges inherent in deploying IoT technologies, drawing on global examples to illustrate variations in implementation and impact.

The first major theme concerns empirical evidence and comparative outcomes of IoT adoption. A growing body of literature demonstrates that IoT applications significantly enhance efficiency, productivity, and sustainability across multiple sectors. For instance, Pushpavalli et al. (2024) reported that the use of IoT technologies and Wireless Sensor Networks (WSN) in precision agriculture led to measurable improvements in crop yields while simultaneously reducing resource inputs such as water and fertilizers. By enabling real-time data collection and monitoring, IoT empowers farmers to make timely and evidence-based decisions, thereby optimizing agricultural productivity while minimizing environmental impact. Similar findings are evident in the urban energy sector, where Raaj et al. (2024) developed an IoT-enabled smart lighting system that reduced energy consumption in urban infrastructure through real-time environmental monitoring and adaptive lighting controls. These examples collectively illustrate the capacity of IoT to contribute to both economic and environmental goals.

Comparisons of IoT implementation between developed and developing nations reveal significant differences in focus, scope, and outcomes. In advanced economies, Liu et al. (2019) demonstrated that IoT deployment is often oriented toward sophisticated technological innovations and integrated systems designed to maximize industrial productivity and energy efficiency. Urban centers in these regions benefit from robust infrastructure that supports seamless IoT integration (Osorio-de-la-Rosa et al., 2019). By contrast, in developing contexts, IoT adoption tends to prioritize affordable, scalable solutions that address pressing challenges such as limited infrastructure and constrained access to essential resources. For example, Uddin et al. (2024) highlighted the use of IoT for worker attendance monitoring in industrial settings, providing a cost-effective method for improving labor management in resource-limited environments. These findings underscore that while IoT is globally relevant, its applications are highly context-dependent, shaped by local infrastructure, economic capacity, and societal needs.

The second theme centers on factors and statistics that influence IoT outcomes. Several factors have emerged as particularly influential, including the availability of technological infrastructure, societal readiness for digital adoption, and the presence of supportive policy frameworks. In the healthcare sector, for instance, the adoption of IoT technologies is contingent upon both the willingness of healthcare providers to integrate digital solutions and the readiness of patients to engage with new forms of monitoring (Figueroa-Lorenzo et al., 2019). The need for robust security mechanisms is critical in this context, as Kerrison et al. (2023) emphasized that data privacy concerns remain one of the primary barriers to IoT adoption in medical applications. Similarly, Erofeeva (2025) identified energy management as a determinant of success in urban IoT projects, demonstrating that energy-efficient design is essential for the long-term viability of smart city systems.

Statistical evidence further reinforces these insights, providing quantitative measures of IoT's contributions. Global estimates suggest that IoT applications in agriculture can increase efficiency by as much as 30% in terms of water and input usage, highlighting the technology's role in addressing food security challenges (Tarrés-Puertas et al., 2023). In the context of urban energy management, Saleem et al. (2024) reported that cities implementing IoT-based systems achieved reductions in energy consumption ranging from 15% to 20% through data-driven optimization. On a broader scale, the integration of IoT with digital technologies has been linked to accelerated economic growth, with Vairagade and Brahmananda (2021) attributing gains in gross domestic product (GDP) to innovations driven by IoT adoption. These figures highlight the global significance of IoT not only as a technological innovation but also as a driver of socio-economic transformation.

The third theme focuses on regional comparisons of IoT outcomes. Studies reveal that geographic context plays a crucial role in shaping the design, implementation, and effectiveness of IoT systems. For example, Lopes et al. (2024) investigated the use of LoRa-based IoT platforms for soil parameter monitoring in Europe, reporting promising outcomes in terms of water conservation for agriculture. Although specific percentages of water savings were not provided, the study demonstrated the potential of IoT to support sustainable agricultural practices in water-stressed regions. In contrast, Pushpavalli et al. (2024) emphasized the application of IoT monitoring systems in India, where resource limitations necessitated the development of affordable and contextually appropriate solutions. These findings suggest that while IoT can deliver substantial benefits in diverse settings, its design and implementation must be tailored to local infrastructural and socio-economic realities.

Quantitative evidence also demonstrates the influence of systemic factors on IoT implementation across regions. Conti et al. (2022) showed that the deployment of IoT-enabled energy systems in data centers could significantly enhance operational efficiency, with the potential to reduce energy consumption on a large scale. Such findings highlight the role of supportive energy policies and institutional commitment in maximizing IoT's potential. Similarly, Cheng et al. (2024) found that integrating IoT with risk management systems for food supply chains enabled countries to increase productivity while simultaneously reducing food waste. These examples illustrate how systemic factors—including policy frameworks, infrastructure development, and societal engagement—directly affect the outcomes of IoT projects.

Taken together, these results underscore the complexity of IoT adoption, which is shaped by a confluence of technological, economic, and social factors. Empirical evidence demonstrates clear benefits in terms of efficiency, productivity, and sustainability, yet these benefits manifest differently depending on context. Developed nations often leverage advanced infrastructure to achieve higher levels of technological sophistication, while developing nations prioritize accessible solutions that address immediate challenges. At the same time, systemic factors such as supportive policies, community involvement, and security frameworks are essential in translating technological potential into tangible outcomes. By synthesizing evidence across diverse settings, this review highlights both the universality and the variability of IoT's impact, offering insights into how the technology can be harnessed to advance global development goals

The findings of this review broadly align with existing literature on the effectiveness of Internet of Things (IoT) applications across multiple domains, while also highlighting key divergences based on context. Studies such as those by Osorio-de-la-Rosa et al. (2019) have demonstrated the transformative potential of sensor-based IoT systems in enhancing efficiency and productivity within agriculture and energy management. These results resonate with the empirical evidence presented in this review, where precision agriculture and smart city initiatives illustrate the measurable benefits of IoT adoption. However, notable differences emerge when the geographic and socio-economic contexts of adoption are considered. Whereas research from developed nations emphasizes advanced infrastructure and high-tech solutions, the present findings underscore the need for affordable and contextually relevant innovations in developing regions, where infrastructural limitations and resource scarcity remain pervasive. This divergence underscores the importance of situating IoT adoption within the specific conditions of each region rather than assuming universal applicability.

The comparison between advanced and resource-constrained settings reveals important nuances in IoT adoption strategies. In urban centers of developed nations, IoT deployment often focuses on achieving high levels of integration and efficiency, supported by sophisticated digital infrastructures. In contrast, studies such as Uddin et al. (2024) demonstrate that in developing countries, IoT initiatives frequently prioritize basic needs, such as attendance monitoring or agricultural resource management, which provide immediate and practical solutions despite infrastructural challenges. The variation in focus highlights the adaptability of IoT as a framework but also underscores the risk of perpetuating digital divides if solutions are not appropriately tailored to the needs and capacities of different populations. This observation aligns with the argument of Pushpavalli et al. (2024), who emphasize the necessity of designing IoT systems that are both accessible and affordable to ensure equitable benefits across diverse contexts.

Systemic and policy-related factors play a decisive role in shaping the success of IoT adoption. Research has shown that government support, through policy stability and investment in digital infrastructure, significantly accelerates the deployment of IoT technologies (Kerrison et al., 2023; Кумар et al., 2025). In the healthcare sector, for instance, Kerrison et al. (2023) highlight that supportive regulatory frameworks are essential in enabling IoT-enabled rural healthcare services, particularly by fostering community engagement and legitimizing digital health practices. Without such systemic backing, IoT initiatives often remain confined to pilot projects, unable to transition into sustainable, large-scale implementations. Similarly, in the energy sector, policies promoting smart grid adoption and renewable integration have been instrumental in ensuring the long-term viability of IoT-driven energy management systems (Erofeeva, 2025). These findings collectively underscore the necessity of aligning technological innovation with supportive governance structures.

Beyond policy, societal acceptance emerges as a critical determinant of IoT effectiveness. The literature consistently emphasizes that public trust is essential for widespread adoption of IoT-based systems, particularly those involving sensitive personal data. For example, resistance to smart metering systems in some contexts has been attributed to concerns over data privacy, surveillance, and potential misuse (Figueroa-Lorenzo et al., 2019). Building trust requires transparency in data usage, effective communication of benefits, and tangible demonstrations of value to end-users. This dimension of social acceptance reinforces the argument that IoT implementation is not solely a technological endeavor but also a socio-cultural process that requires engagement, inclusivity, and responsiveness to public concerns.

The review also brings attention to potential solutions proposed in the literature to address persistent barriers to IoT adoption. Blockchain technology has been widely recommended as a mechanism to safeguard data integrity and user privacy, particularly in healthcare applications (Kerrison et al., 2023). While theoretical models and simulations provide promising indications of blockchain's potential, empirical studies validating its effectiveness in large-scale, real-world IoT deployments remain limited. Similarly, Vairagade and Brahmananda (2021) propose machine learning-driven methods for improving IoT service quality through predictive analytics and adaptive optimization. However, the lack of extensive field testing raises questions about the scalability and practical viability of these solutions across diverse contexts. The absence of empirical evidence suggests that while innovation is abundant in the theoretical domain, there is a pressing need for systematic evaluations that examine the real-world performance of proposed solutions.

Another layer of complexity lies in the systemic interplay between technological innovation and broader socio-economic dynamics. As highlighted by Saleem et al. (2024) and Tarrés-Puertas et al. (2023), IoT can deliver quantifiable benefits such as reductions in energy consumption and improvements in agricultural efficiency. However, the extent to which these benefits are realized depends heavily on structural factors such as infrastructure quality, education systems, and economic capacity. In developing contexts, inadequate digital literacy and limited access to reliable connectivity can severely constrain the impact of IoT, despite the availability of promising technologies. This systemic dependency suggests that efforts to scale IoT must be accompanied by investments in education, capacity building, and infrastructural development to create enabling environments for sustainable adoption.

The interplay between systemic conditions and technological capacity also highlights a significant limitation of existing literature. Much of the research remains focused on technical feasibility, often at the expense of addressing socio-economic and policy dimensions. While pilot projects and simulations offer valuable insights, they do not fully capture the complexities of real-world implementation, particularly in resource-constrained environments. As noted by Shahra et al. (2019) and Papatsimouli et al. (2023), the translation of IoT innovations into sustainable practices in sectors such as healthcare and agriculture has proven challenging, owing to contextual barriers that are often overlooked in technology-centric studies. This limitation points to the necessity of interdisciplinary research that bridges technical, social, and policy perspectives, ensuring that proposed solutions are both technologically sound and socially viable.

The literature further underscores the need for longitudinal studies that assess the long-term impacts of IoT adoption. Most existing research provides short-term evaluations of efficiency gains or productivity improvements but falls short of examining sustainability over extended periods. For example, while Conti et al. (2022) document significant energy savings in IoT-enabled data centers, it remains unclear whether such savings can be maintained as systems scale and as new challenges emerge, such as increased demand for data processing or evolving cybersecurity threats. Long-term studies would provide critical insights into the durability of IoT's benefits and the potential unintended consequences of widespread adoption.

Addressing these limitations requires a concerted research agenda that prioritizes empirical validation, interdisciplinary integration, and contextual sensitivity. Systematic reviews, meta-analyses, and cross-country comparative studies could help build a more comprehensive understanding of IoT adoption across diverse contexts. Additionally, partnerships between academic institutions, industry stakeholders, and policymakers are essential for generating evidence-based solutions that are both innovative and implementable. Without such collaborative approaches, the risk persists that IoT will remain a fragmented and unevenly distributed innovation, benefiting some regions and populations while marginalizing others.

CONCLUSION

This review highlights the transformative potential of the Internet of Things (IoT) in reshaping sectors such as healthcare, agriculture, energy management, and urban governance. Empirical evidence demonstrates significant efficiency gains, ranging from improved crop yields and water conservation to reduced energy consumption in smart cities. Comparative analysis underscores the context-dependent nature of IoT adoption: developed nations leverage advanced infrastructures for high-tech integration, while developing countries focus on affordable, contextually relevant solutions to address resource limitations. Discussion further revealed that systemic factors—particularly supportive policy frameworks, public trust, and infrastructural readiness—are decisive in determining the success of IoT projects. Persistent challenges remain in ensuring security, energy efficiency, and interoperability, with blockchain and machine learning proposed as promising but under-validated solutions. To address these issues, governments should invest in digital infrastructure, develop regulatory frameworks that safeguard privacy, and promote community engagement to build trust in IoT systems. Future research must extend beyond technical feasibility to examine long-term sustainability, socio-economic impacts, and the scalability of solutions across diverse contexts. In sum, IoT offers substantial opportunities for advancing global development goals, but its success depends on bridging systemic gaps and fostering inclusive, evidence-based strategies that align with local and global prioritie.

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