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DISCOVERING SUSTAINABLE ECOSYSTEM WITH GREEN IOT - SMART CITIES AND TECHNOLOGICAL INFRASTRUCTURE

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Master's Thesis

Supevisor

Assoc. Prof. Dr. Abdullahi Abdu IBRAHIM

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The thesis titled DISCOVERING SUSTAINABLE ECOSYSTEM WITH GREEN IOT- SMART CITIES AND TECHNOLOGICAL INFRASTRUCTURE prepared by SYED MUSTAFA SHAH and submitted on 15/05/2025 has been **accepted unanimously** for the degree of Master of Science in Information Technologies.

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I hereby declare that all information/data presented in this graduation project has been obtained in full accordance with academic rules and ethical conduct. I also declare all unoriginal materials and conclusions have been cited in the text and all references mentioned in the Reference List have been cited in the text, and vice versa as required by the abovementioned rules and conduct.

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DEDICATION

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ABSTRACT

DISCOVERING SUSTAINABLE ECOSYSTEM WITH GREEN IOT - SMART CITIES AND TECHNOLOGICAL INFRASTRUCTURE

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Internet of things (IoT) is one of the most extensively used concepts that enables large numbers of connected devices to obtain data, analyse it, and utilize it. However, the increased connectivity of objects and devices in IoT brings serious environmental problems, namely those connected with power consumption and e-waste generation. This paper aims to examine the possibility of "Green IoT" which encompasses using efficient energy technologies, recycled/reusable materials, and green energy to reduce the adverse effects IoT could cause to the environment. Case studies and real-world applications are used in the research where energy-efficient designs of Green IoT technologies are studied to show that Green IoT technologies can drastically minimize energy use, control emissions, and promote a more sustainable IoT environment. Several papers have been studied and some of the areas of contribution include enabling technologies which include Green Radio Frequency Identification (RFID), energy harvester devices, low power communication protocol, all of which enable improvement of energy efficiency in the IoT systems across smart cities, healthcare, and industrial automation. Furthermore, this paper outlines key issues arising from the application of Green IoT, including lack of protocol coordination and ineffective policy measures. The results confirm Green IoT as a viable solution regarding concerns over the lack of sustainability in IoT interventions and provide potential directions and strategies for policy makers and executives on how to create a less damaging footprint of IoT while making the most of the opportunities such technologies offer for the improvement of the quality of life and the creation of sustainable development.

Keywords: Green IoT; Sustainable IoT Ecosystems; Energy-Efficient Technologies; Electronic Waste (E-Waste); Renewable Energy Integration.

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ABBREVIATIONS

ACO	:	Ant Colony Optimization
AI	:	Artificial Intelligence
AMI	:	Advanced Metering Infrastructure
BMS	:	Business Management System
CMOS	:	Complementary Metal-Oxide-Semiconductor
DVFS	:	Dynamic Voltage and Frequency Scaling
EV	:	Electric Vehicle
E-waste	:	Electronic Waste
GA	:	Genetic Algorithm
GCC	:	Green Cloud Computing
GDC	:	Green Data Centre
G-M2M	:	Green Machine-to-Machine
GWSN	:	Green Wireless Sensor Networks
HVAC	:	Heating, Ventilation, and Air Conditioning
IC	:	Integrated Circuit
ICT	:	Information and Communications Technology
IEA	:	International Energy Agency
IoT	:	Internet of Things
ISO	:	Internation Organization for Standardization
ITU	:	Internation Telecommunication Union
LCA	:	Life Cycle Assessment
LPWAN	:	Low Power Wide Area Network
MAC	:	Media Access Control

MCU	:	Microcontroller Unit
ML	:	Machine Learning
MM	:	Multimedia
NB-IoT	:	Narrowband Internet of Things
PUE	:	Power Usage Effectiveness
RFID	:	Radio Frequency Identification
SDG	:	Sustainable Development Goals
UAV	:	Unmanned Aerial Vehicle
UNEP	:	United Nations Environment Programme
UNFCCC	:	United Nations Framework Convention on Climate Change
VM	:	Virtual Machine
WHO	:	World Health Organization
WSN	:	Wireless Sensor Network

1. INTRODUCTION

1.1 BACKGROUND

1.1.1 Introduction to IoT Technologies

The Internet of Things (IoT) is a revolutionary concept that has gained significant traction in recent years, promising to transform various aspects of our lives and industries. At its core, IoT refers to a network of interconnected physical devices or "things" embedded with sensors, actuators, and communication capabilities that enable them to collect, exchange, and analyse data autonomously. These devices can range from simple household appliances and wearable gadgets to sophisticated industrial machinery and infrastructure components.

IoT operates through a systematic process:

a. Data Acquisition: IoT devices equipped with sensors gather data about their environment or specific parameters.

b. Connectivity: These devices utilize communication technologies like Wi-Fi, Bluetooth, or cellular networks to connect to the internet.

c. Data Processing and Analysis: The collected data is transmitted to cloud-based platforms or edge computing systems, where it undergoes processing and analysis using algorithms and analytics tools.

d. Decision Making and Action: Insights derived from the data analysis drive decision-making processes within the IoT system, triggering automated actions or providing recommendations.

e. Feedback Mechanism: Continuous monitoring and evaluation of the system's performance enable real-time adjustments and optimizations, ensuring ongoing improvement and efficiency.

In essence, IoT devices collect data, which is then analysed and used to make informed decisions or trigger actions, with the system constantly learning and adapting through feedback mechanisms. This process forms the foundation of IoT technology, enabling its widespread applications across various domains.

1.1.2 Growth and Evolution of IoT

The evolution of the Internet of Things (IoT) has been driven by a convergence of technological advancements, market forces, and societal needs. Schaffers et al. emphasize the transformative potential of IoT in creating "smart" environments that are responsive, adaptive, and efficient [17]. From its origins as a conceptual framework to its status as a pervasive technology, IoT has reshaped various industries and redefined the way we interact with the world around us. The democratization of connectivity, coupled with advancements in wireless communication and sensor technology, has enabled the proliferation of IoT applications across diverse domains [50].

Smart cities have emerged as a focal point for IoT deployment, leveraging sensor networks, data analytics, and automation to enhance urban infrastructure and services [26]. The advent of edge computing further accelerates IoT's evolution by enabling real-time processing and decision-making at the network's edge, unlocking new possibilities for IoT applications in remote and resource-constrained environments [16].

1.2 PROBLEM STATEMENT

1.2.1 Environmental Impact of IoT

The widespread adoption of Internet of Things (IoT) devices has raised significant concerns about their environmental impact. IoT devices, ranging from small sensors to large-scale infrastructure, contribute to increased energy consumption and electronic waste generation, posing challenges to environmental sustainability [40].

IoT devices often operate continuously, leading to significant power consumption, which results in higher energy demands and increased carbon emissions, exacerbating environmental degradation [14]. Additionally, the production, use, and disposal of IoT devices contribute to the growing problem of electronic waste, posing environmental and health risks and highlighting the need for sustainable solutions [40].

Addressing the environmental impact of IoT requires the development and adoption of sustainable practices. Green IoT, an emerging concept, focuses on designing and implementing IoT solutions that prioritize energy efficiency and environmental sustainability [51]. By integrating Green IoT principles, such as energy-efficient design and renewable energy usage, it is possible to minimize the negative environmental effects associated with IoT deployment while maximizing the benefits of these technologies.

1.2.2 Energy Consumption and Carbon Footprint

The rapid growth of IoT devices has significantly increased energy consumption due to their continuous operation and constant data transmission. IoT devices, from smart home appliances to industrial sensors, rely heavily on electricity, leading to a growing demand for energy resources.

1.2.2.1 Energy consumption trends

Recent studies highlight the critical energy consumption concerns of IoT. Andrae and Edler indicate that the Global Information and Communication Technology (ICT) sector, including IoT, could account for up to 21% of the world's total electricity usage by 2030 if current trends persist [4]. This demand is driven by both the number of devices and the energy requirements of data centers that store and process the data generated by these devices.

1.2.2.2 Factors contributing to energy consumption

Several factors contribute to the high energy consumption of IoT devices:

a. Continuous Operation: Many IoT devices operate continuously, leading to constant power usage.

b. Data Transmission and Processing: Real-time data transmission and the energy demands of data centres contribute significantly to energy consumption [34].

c. Battery Life: The demand for longer battery life in portable devices often results in higher energy usage during the charging process [10].

1.2.2.3 Carbon footprint of IoT

The carbon footprint of IoT is linked to its energy consumption. The generation of electricity, particularly from fossil fuels, contributes to carbon emissions. The ICT sector, including IoT, could contribute up to 3.5% of global carbon emissions by 2025 [24].

1.2.2.4 Impact on the environment

The environmental impact of IoT includes:

a. Greenhouse Gas Emissions: Increased energy consumption leads to higher greenhouse gas emissions.

b. Resource Depletion: The production and disposal of IoT devices require significant resources [3].

c. Electronic Waste: Rapid obsolescence of devices results in substantial electronic waste [23].

1.2.2.5 Sustainable solutions for energy consumption

To mitigate the energy consumption and carbon footprint of IoT, several sustainable solutions are being explored:

a. Energy-Efficient Design: Developing low-power components and optimizing software for minimal energy usage [50].

b. Renewable Energy Sources: Using renewable energy sources such as solar or wind power for IoT devices and data centres [32].

c. Energy Harvesting: Implementing systems that generate power from ambient sources, such as kinetic or thermal energy [41].

d. Smart Grid Integration: Enhancing energy efficiency by optimizing energy distribution through smart grid technology [46].

1.2.2.6 Policy and regulatory measures

Effective policy and regulatory measures are crucial:

a. Incentives for Green IoT: Governments can provide incentives for companies implementing energy-efficient IoT solutions [51].

b. Energy Efficiency Standards: Establishing and enforcing standards for IoT devices to drive greener technology development [51].

1.2.3 Electronic Waste and Resource Depletion

The rapid growth of the Internet of Things (IoT) has significantly increased the number of connected devices, leading to enhanced efficiencies and innovations across various sectors. However, this surge in IoT device deployment has also brought about significant environmental concerns, particularly regarding electronic waste (e-waste) and resource depletion.

1.2.3.1 Electronic waste (e-waste)

The term electronic waste (e-waste) refers to discarded electrical or electronic devices. With the proliferation of IoT, the volume of e-waste has surged. E-waste contains hazardous materials such as lead, mercury, and cadmium, which pose severe environmental and health risks when not effectively managed. According to the *Global E-waste Monitor 2020*, global e-waste reached a record 53.6 million metric tons in 2019, with only 17.4% being formally documented as collected and recycled [47]. This underscores the challenges in managing the lifecycle of IoT devices. Moreover, improper disposal of e-waste leads to soil, water, and air pollution, adversely affecting ecosystems and human health [26].

1.2.3.2 Resource depletion

The manufacturing of IoT devices necessitates a variety of precious and rare-earth metals, including gold, silver, platinum, and palladium. The extraction and processing of these materials are energy-intensive and lead to significant environmental degradation. The demand for these metals is expected to rise sharply with the continued growth of IoT, exacerbating resource depletion. A report by the United Nations Environment Programme (UNEP) highlights that the global demand for metals like cobalt and lithium, essential for batteries in IoT devices, is projected to increase drastically, leading to potential supply shortages and environmental harm [43]. Additionally, mining activities required to extract these metals contribute to deforestation, loss of biodiversity, and soil erosion [25].

1.2.3.3 Addressing e-waste and resource depletion through green IoT

To mitigate the environmental impact of IoT, adopting Green IoT practices is crucial. Strategies include:

a. Energy-Efficient Design: Developing devices with low-power consumption to extend their lifecycle and reduce the frequency of replacements.

b. Recycling and Reuse: Implementing robust recycling programs and promoting the reuse of components from decommissioned devices.

c. Energy Harvesting: Utilizing renewable energy sources such as solar or kinetic energy to power IoT devices, reducing reliance on conventional batteries [51].

d. Sustainable Manufacturing: Sourcing materials responsibly and adopting manufacturing processes that minimize environmental impact.

1.2.4 Lack of Sustainable IoT Practices

The rapid growth of IoT technologies has revolutionized various sectors, but it has also led to significant environmental concerns. The deployment and operation of IoT devices contribute to increased energy consumption and electronic waste, posing substantial environmental challenges.

1.2.4.1 Energy consumption and inefficiency

One of the primary environmental concerns associated with IoT is the significant energy consumption of devices. Many IoT devices are designed to operate continuously, leading to high energy usage. The energy consumption of IoT devices is a critical issue, particularly in large-scale deployments [30]. Energy-intensive operations, such as continuous data transmission and processing, exacerbate the problem. The global energy consumption by data centers and networked devices is expected to rise significantly, contributing to increased greenhouse gas emissions [18]. Despite the known environmental impacts, many IoT devices are not optimized for energy efficiency, leading to unnecessary energy consumption. Energy-efficient designs, such as the use of low-power components and optimized software, are not widely adopted in the industry due to cost constraints and the focus on rapid product development and deployment [6].

1.2.4.2 Electronic waste and disposal issues

The proliferation of IoT devices has also led to a surge in electronic waste (e-waste). IoT devices, like other electronic gadgets, have limited lifespans and are often disposed of after a few years of use. In 2019, e-waste generated globally reached 53.6 million metric tons, with IoT devices being a notable contributor [47]. The improper disposal of e-waste leads to hazardous substances leaking into the environment, causing soil and water pollution, and posing health risks to humans and wildlife. Another major issue is the inadequate recycling and disposal policies for IoT devices. Many countries lack comprehensive policies and frameworks to manage the disposal and recycling of e-waste effectively. As a result, a large portion of e-waste ends up in landfills or is processed in informal recycling facilities, which often lack the necessary infrastructure to handle hazardous materials safely [7].

1.2.4.3 Limited adoption of green IoT practices

Green IoT practices, which focus on reducing the environmental impact of IoT devices, have not been widely adopted. These practices include the use of renewable energy sources, energy harvesting techniques, and low-power communication protocols. While there is growing awareness of Green IoT, its adoption remains limited due to technological, economic, and regulatory challenges [1]. More research and development are needed to overcome these barriers and promote the widespread implementation of Green IoT practices.

1.2.5 Need for Green IoT Solutions

The rapid proliferation of IoT devices has brought significant environmental challenges. IoT devices, often designed to operate continuously, contribute to energy consumption. According to the International Energy Agency (IEA), connected devices account for over 5% of global electricity use, a figure expected to rise with increased IoT adoption [19]. This high energy consumption translates into higher carbon emissions, contributing to climate change.

Additionally, the production and disposal of IoT devices generate substantial electronic waste (e-waste). The Global E-waste Monitor 2020 reported that approximately 53.6 million metric tons of e-waste were generated worldwide in 2019, with a sizable portion attributed to the rise of connected devices [47]. This e-waste contains hazardous materials that pose environmental and health risks if not responsibly managed.

1.2.5.1 Economic and social implications

The environmental impact of IoT extends beyond ecological damage to include economic and social implications. Energy inefficiency in IoT systems can lead to higher operational costs for businesses and consumers. Inefficient energy use in smart home devices, for instance, can result in increased electricity bills, burdening consumers [35]. Furthermore, improper disposal of IoT devices exacerbates the global e-waste crisis, leading to severe health hazards in regions where e-waste is dumped or improperly recycled [28].

1.2.5.2 Strategies for green IoT

Addressing these challenges necessitates the adoption of Green IoT solutions, focusing on minimizing the environmental footprint of IoT technologies while maintaining their functional benefits. This involves strategies such as developing energy-efficient devices, implementing low-power communication protocols, and utilizing renewable energy sources.

Energy-efficient device design is crucial for reducing power consumption. Techniques like dynamic power management and energy-aware computing can significantly enhance the energy efficiency of IoT systems [31].

Low-power communication protocols like Zigbee, LoRa, and Narrowband IoT (NB-IoT) drastically reduce the energy required for data transmission [42]. These protocols operate over long distances with minimal power, making them ideal for IoT applications in remote and resource-constrained environments.

Energy harvesting technologies capture ambient energy from the environment to power IoT devices. By integrating solar, thermal, and kinetic energy harvesting, IoT devices can operate sustainably without relying on traditional power sources [52].

1.2.5.3 Policy and regulatory measures

Effective policy and regulatory frameworks are essential for promoting the adoption of Green IoT solutions. Governments can incentivize energy-efficient IoT technologies through subsidies, tax breaks, and grants [7]. Establishing industry standards for energy consumption and e-waste management can drive manufacturers to prioritize sustainability in their IoT products.

1.2.6 Challenges in Implementation

The implementation of Green IoT solutions faces several technological challenges. One significant issue is the development of energy-efficient hardware. IoT devices typically require continuous operation, demanding innovative designs that consume minimal power. Achieving this involves integrating low-power processors and optimizing software to reduce energy consumption without compromising performance. Current advancements in semiconductor technology and microcontrollers are helping, but the balance between energy efficiency and computational power remains a key challenge [50].

1.2.6.1 Communication protocols

Another challenge lies in the communication protocols used by IoT devices. Traditional protocols, such as Wi-Fi and Bluetooth, are not optimized for low power consumption over extended periods. Developing and standardizing low-power communication protocols like Zigbee, LoRa, and NB-IoT is essential for reducing energy use in IoT networks. However, ensuring interoperability and maintaining data integrity and security with these protocols pose significant hurdles [7].

1.2.6.2 Energy harvesting

Energy harvesting techniques, such as solar, kinetic, and thermal energy conversion, offer promising solutions to power IoT devices sustainably. However, these methods face practical challenges, including inconsistent energy availability and efficiency of conversion processes. For example, solar energy is dependent on weather conditions and the geographical location of the device, while kinetic energy harvesting requires sufficient motion, which may not be feasible in all scenarios [41]. Research and development in this area are ongoing to improve the reliability and efficiency of these energy sources.

1.2.6.3 Data management and processing

The vast amounts of data generated by IoT devices necessitate efficient data management and processing frameworks. Processing this data in real-time while ensuring low energy consumption is a significant challenge. Edge computing and fog computing have been proposed as solutions to this issue, bringing data processing closer to the data source to reduce latency and energy use. However, these approaches require substantial infrastructure changes and face scalability issues [33].

1.2.6.4 Economic and financial challenges

Implementing Green IoT solutions also involves economic and financial challenges. The initial costs of developing and deploying energy-efficient IoT systems can be high. This includes the cost of advanced hardware, research and development, and the integration of modern technologies into existing systems. Small and medium-sized enterprises (SMEs) might find it challenging to invest in these technologies without substantial financial incentives or support [29].

1.2.6.5 Policy and regulatory challenges

Regulatory frameworks and policies play a crucial role in the adoption of Green IoT solutions. However, the lack of standardized regulations and policies across different regions can hinder implementation. Governments and regulatory bodies need to develop clear guidelines and standards for energy-efficient IoT deployments. Additionally, policies should incentivize the adoption of sustainable practices through subsidies, tax breaks, and grants for research and development [4].

1.2.6.6 Security and privacy concerns

Security and privacy are critical concerns in IoT implementations. Ensuring that data transmitted and stored by IoT devices is secure while maintaining user privacy requires robust encryption and authentication mechanisms. Energy-efficient security solutions need to be developed to ensure that implementing security measures does not significantly increase energy consumption [38].

1.2.6.7 Integration with existing systems

Integrating Green IoT solutions with existing systems and infrastructure can be challenging. Many current systems were not designed with energy efficiency in mind and retrofitting them with modern technologies can be complex and costly. Ensuring compatibility and seamless operation between new and existing systems requires careful planning and execution [9].

1.3 RESEARCH OBJECTIVES

This study aims to contribute to the development of sustainable IoT practices through the following objectives:

a. Identification and Evaluation of Green IoT Enabling Technologies: Examine essential technologies such as Green Radio-Frequency Identification (RFID), Green Wireless Sensor Networks (GWSN), Green Cloud Computing (GCC), Green Machine to Machine (G-M2M) communication, and Green Data Centres (GDC) in the role of improved energy efficiency and sustainability on IoT systems.

b. Assessment of Energy Consumption Models in Cloud Computing: We analyse current energy consumption models on cloud computing components such as data centres, transport networks, and customer operated devices, and propose strategies to lower carbon footprint of cloud based IoT services.

c. Energy Efficiency Analysis in IoT Deployments: It consists of evaluating current energy consumptions practices as adopted in IoT system and consider narrow options for improvement of energy consumption employing some green technologies in reduction of such environmental impact.

d. Application Analysis of Green IoT in Key Sectors: Analyse the deployment of Green IoT technologies in various sectors such as smart cities, healthcare, transportation, and energy management, by examining sector peculiarities of benefits, problems, and their effect on overall sustainability.

e. Identification of Challenges and Future Directions for Green IoT: Analyse the primary challenges including technical, economic, and social barriers to Green IoT adoption in disregard and offer recommendations and pathways for future research allowing Green IoT to play a more central role in supporting sustainability.

1.4 SIGNIFICANCE OF THE STUDY

The integration of sustainability principles into IoT deployment is crucial for ensuring that technological advancements do not come at the expense of the environment. This study aims to contribute to the development of sustainable IoT practices that can help mitigate the environmental impact while fostering technological innovation. The findings will be valuable for policymakers, industry leaders, and researchers interested in promoting eco-friendly IoT solutions.

1.5 RESEARCH QUESTIONS

This research seeks to answer the following questions:

i. What are the key technologies that enable Green IoT, and how can they be integrated into existing IoT systems?

ii. How can energy consumption in IoT systems be effectively measured and reduced?

iii. What are the challenges and opportunities in implementing Green IoT technologies?

iv. How do Green IoT technologies impact the overall performance and reliability of IoT systems?

v. What future research directions should be pursued to further enhance the sustainability of IoT and smart grid technologies?

1.6 SCOPE AND LIMITATIONS

1.6.1 Scope of the Study

This study aims to comprehensively investigate the concept of Green Internet of Things (IoT) and its potential applications in promoting sustainability and energy efficiency. The scope of this study includes:

a. Theoretical Frameworks: Exploring existing theoretical frameworks and models related to Green IoT, including energy-efficient protocols, sustainable design principles, and environmental impact assessment methodologies.

b. Enabling Technologies: Analysing key enabling technologies for Green IoT, such as Green RFID, GWSN, GCC, G-M2M, and GDC, to understand their principles and integration possibilities.

c. Energy Efficiency Analysis: Examining theoretical models and strategies for measuring and optimizing energy consumption in IoT systems, focusing on theoretical approaches to reduce energy usage without compromising functionality.

d. Applications in Various Sectors: Investigating theoretical frameworks and case studies to understand how Green IoT can be applied in different sectors such as smart cities, healthcare, transportation, and energy management to promote sustainability and efficiency.

e. Challenges and Opportunities: Identifying theoretical challenges and opportunities in implementing Green IoT technologies, including technical, economic, and social barriers, and theoretical strategies to overcome these challenges.

f. Future Directions: Proposing theoretical future research directions and recommendations for policymakers, industries, and stakeholders to further enhance the sustainability and efficiency of Green IoT systems.

1.6.2 Limitations of the Study

a. Theoretical Nature: As this study primarily focuses on theoretical exploration, there will be minimal practical work or data analysis involved. The findings and recommendations are based on theoretical frameworks and existing literature.

b. Limited Exploration of Implementation Challenges: While this study identifies theoretical challenges in implementing Green IoT technologies, it may not extensively explore the practical intricacies and complexities involved in overcoming these challenges. Theoretical frameworks may overlook nuanced implementation barriers that could affect the feasibility and success of Green IoT initiatives in real-world contexts.

c. Data Availability: Limited availability of empirical data may restrict the depth of analysis and validation of theoretical models and frameworks proposed in this study.

d. Scope Constraints: Due to the vast scope of Green IoT and its interdisciplinary nature, certain aspects of the topic may not be covered comprehensively within the confines of this theoretical study.

e. Dynamic Field: The field of Green IoT is rapidly evolving, and new technologies, challenges, and opportunities may emerge after the completion of this study, which may not be addressed within the theoretical framework established herein.

Despite these limitations, this theoretical study aims to provide valuable insights and theoretical foundations for further research and practical implementation of Green IoT technologies to promote sustainability and energy efficiency.

1.7 STRUCTURE OF THE THESIS

The thesis is structured as follows:

a. Introduction

b. Literature Review

c. Methodologies

d. Results and Discussion

e. Conclusions and Recommendations

2. LITERATURE REVIEW

2.1 ENVIRONMENTAL IMPACT OF IOT TECHNOLOGIES

The rapid proliferation of Internet of Things (IoT) technologies has brought about significant transformations across various sectors, revolutionizing industries through enhanced connectivity and data-driven decision-making processes. However, alongside the numerous benefits, the widespread deployment of IoT devices has raised concerns regarding their environmental impact. This section examines the key environmental challenges associated with IoT technologies, including energy consumption, electronic waste generation, and resource depletion.

2.1.1 Energy Consumption in IoT Devices

IoT devices are characterized by their constant connectivity and data processing capabilities, resulting in continuous energy consumption. The energy demands of these devices, from data transmission to processing, contribute to increased electricity consumption and carbon emissions. Moreover, the proliferation of IoT applications in sectors such as smart homes, healthcare, and industrial automation exacerbates the energy consumption challenge.

According to recent studies, IoT devices are estimated to consume significant amounts of energy, with projections indicating a substantial increase in energy demand as IoT adoption continues to grow [2]. For instance, a study by GeSI and The Shift Project estimates that the ICT sector, including IoT devices, could account for up to 14% of global greenhouse gas emissions by 2040 if left unchecked [15].

2.1.2 Electronic Waste Generation

Another environmental concern associated with IoT technologies is the generation of electronic waste (e-waste). As IoT devices become obsolete or reach the end of their lifecycle, they contribute to the growing volume of e-waste, posing challenges for disposal and recycling. The rapid pace of technological advancements and shorter product lifecycles further exacerbate the e-waste problem, leading to environmental pollution and resource depletion.

Recent reports highlight the increasing volume of e-waste generated worldwide, with IoT devices contributing significantly to this trend. For instance, the Global E-waste Monitor 2020 estimates that 53.6 million metric tons of e-waste were generated globally in 2019, with IoT devices representing a considerable portion of this waste stream [7].

2.1.3 Resource Depletion and Environmental Degradation

The production and disposal of IoT devices also have implications for resource depletion and environmental degradation. The extraction of raw materials, such as rare earth metals and minerals, for the manufacturing of IoT components contributes to habitat destruction, deforestation, and water pollution. Additionally, improper disposal practices, including landfilling and incineration, further exacerbate environmental degradation and pose risks to human health and ecosystems.

Recent research highlights the need for sustainable approaches to resource extraction and waste management in the context of IoT technologies. For example, a study by Schuetz et al. emphasizes the importance of circular economy principles in mitigating the environmental impact of IoT devices by promoting resource efficiency, recycling, and product reuse [8].

2.2 SUSTAINABLE DEVELOPMENT GOALS AND IOT

The Sustainable Development Goals (SDGs), adopted by all United Nations Member States in 2015 as part of the 2030 Agenda for Sustainable Development, provide a universal framework for addressing global challenges and promoting sustainable development. The 17 SDGs encompass a wide range of objectives, including ending poverty, ensuring access to clean water and sanitation, promoting gender equality, and combating climate change.

2.2.1 Role of IoT in Advancing Sustainable Development Goals (SDGs)

The integration of IoT technologies plays a crucial role in advancing several SDGs by enabling data-driven decision-making, enhancing resource efficiency, and facilitating innovative solutions to complex challenges. IoT applications contribute to various SDGs, including:

a. SDG 2: Zero Hunger: IoT-enabled precision agriculture enhances crop yields, optimizes resource utilization, and improves food security by monitoring soil conditions, water levels, and crop health in real-time [13].

b. SDG 3: Good Health and Well-being: Wearable health monitoring devices and telemedicine platforms powered by IoT technologies facilitate remote patient monitoring, disease prevention, and personalized healthcare services, particularly in underserved areas [49].

c. SDG 7: Affordable and Clean Energy: IoT solutions promote energy efficiency, renewable energy integration, and grid management optimization, thereby accelerating the transition to sustainable energy systems and increasing access to affordable and clean energy sources [20].

d. SDG 11: Sustainable Cities and Communities: Smart city initiatives leverage IoT technologies to improve urban infrastructure, enhance public services, reduce traffic congestion, and promote sustainable urban development through efficient resource management and data-driven decision-making [45].

e. SDG 13: Climate Action: IoT-enabled environmental monitoring systems, smart grid technologies, and energy-efficient solutions contribute to climate change mitigation efforts by reducing greenhouse gas emissions, enhancing disaster resilience, and supporting adaptive measures [44].

2.2.2 Challenges and Opportunities

While IoT offers significant potential for advancing SDGs, several challenges must be addressed to maximize its impact. These include privacy and security concerns, interoperability issues, digital divide disparities, and environmental sustainability considerations [21]. However, through collaborative efforts involving governments, industry stakeholders, civil society organizations, and academia, IoT can serve as a powerful enabler of sustainable development, driving innovation, fostering inclusivity, and promoting resilience in the face of global challenges.

2.3 GREEN IOT: PRINCIPLES AND STRATEGIES

Green IoT, an emerging concept, focuses on designing and implementing IoT solutions that prioritize energy efficiency and environmental sustainability [4]. The importance of Green IoT lies in its potential to mitigate the environmental impact of IoT technologies while maintaining their functionality and effectiveness. By adopting Green IoT principles, it is possible to reduce energy consumption, minimize carbon emissions, and promote eco-friendly practices in IoT deployment [4].

Green IoT encompasses several key principles and strategies aimed at reducing energy consumption and environmental footprint:

a. Energy-Efficient Design: Developing IoT devices with low-power components and optimizing software for minimal energy usage is essential. By leveraging energy-efficient hardware designs and software algorithms, IoT devices can operate with lower power requirements without compromising functionality [50].

b. Low-Power Communication Protocols: Utilizing communication technologies that consume less energy is crucial for Green IoT solutions. Protocols such as Zigbee, LoRa, and NB-IoT are designed to minimize energy consumption during data transmission, making them ideal for IoT applications where power efficiency is paramount [50].

c. Energy Harvesting: Implementing energy harvesting techniques allows IoT devices to generate power from ambient sources such as solar or kinetic energy. By harnessing renewable energy sources, IoT devices can operate autonomously, reducing their reliance on traditional power sources and minimizing their environmental impact [4].

2.4 CASE STUDIES IN GREEN IOT

Several case studies illustrate the application of Green IoT principles:

Pandiyan et al. [37] examine advancements in green Internet of Things (IoT) technologies applied to smart grids, focusing on enhancing sustainability by optimizing energy use, integrating renewable energy, and implementing advanced communication and management systems.

Alsharif et al. [27] provide a comprehensive review of Green IoT, discussing current practices, future research directions, and the integration of green practices within IoT to enhance environmental sustainability.

Memić et al. [5] examine sustainable practices and technologies within the Green IoT framework, discussing how these can be employed to improve environmental sustainability and quality of life through smarter, greener technologies.

Kshirsgar [36] discusses the implementation of green computing within cloud technology platforms, focusing on strategies to reduce energy consumption, enhance system efficiency, and promote environmental sustainability within cloud-based services.

Almalki et al. [11] explore the potential of Green IoT technologies to foster eco-friendly and sustainable developments in smart cities, discussing future directions and opportunities for enhancing environmental sustainability through innovative IoT solutions.

Tushar et al. [48] focus on the use of IoT technologies for green building management, highlighting how IoT can contribute to energy efficiency and sustainability in building operations by optimizing resource use and reducing environmental impacts.

Alsamhi et al. [39] review the current state of Green IoT technologies and their applications across various sectors, emphasizing the role of green practices in enhancing the sustainability of IoT systems and proposing future prospects for developing a greener IoT ecosystem.

Shaikh et al. [12] explore the integration of energy-efficient technologies on the Internet of Things (IoT), focusing on various enabling technologies and applications that contribute to creating a green IoT ecosystem aimed at reducing energy consumption and environmental impact.

Yaacoub et al. [10] investigate energy-efficient techniques in cooperative wireless sensor networks to support the green Internet of Things, focusing on multi-hop data transmission to reduce power consumption and improve delay outcomes compared to non-cooperative scenarios.

Ayre et al. [22] focus on balancing energy consumption in cloud computing, particularly in processing, storage, and transport, to create more energy-efficient systems and reduce the environmental impact of cloud services.

2.5 POLICY AND REGULATORY FRAMEWORKS

Policy and regulatory frameworks play a vital role in shaping the adoption and implementation of Green IoT practices. By providing incentives, establishing standards, and enforcing regulations, governments and regulatory bodies can promote the development and deployment of energy-efficient IoT technologies while ensuring environmental sustainability [16].

2.5.1 Incentives for Adoption

One of the primary ways in which policymakers support Green IoT is by offering incentives to encourage its adoption. These incentives may include tax breaks, subsidies, grants, and other financial incentives aimed at reducing the upfront costs associated with implementing energy-efficient IoT solutions [16]. By providing financial support, governments can incentivize businesses and organizations to invest in Green IoT technologies and accelerate the transition toward a more sustainable IoT ecosystem.

2.5.2 Establishing Standards

Another key aspect of policy support for Green IoT is the establishment of standards and guidelines for energy-efficient IoT design and deployment. Standards bodies and regulatory agencies collaborate with industry stakeholders to develop technical specifications, certification programs, and compliance frameworks that promote energy efficiency and environmental sustainability in IoT systems [16]. These standards help ensure interoperability, reliability, and safety while driving innovation and best practices in Green IoT development.

2.5.3 Environmental Regulations

In addition to incentives and standards, governments can also enact environmental regulations that encourage or require the adoption of Green IoT practices. These regulations may include mandates for energy efficiency, emissions reduction targets, and waste management requirements that apply to IoT devices and systems [16]. By setting clear environmental goals and imposing regulatory obligations, policymakers create a framework that incentivizes businesses to prioritize sustainability in their IoT deployments.

2.5.4 Global Cooperation and Harmonization

Given the global nature of IoT technologies, international cooperation and harmonization of policies and regulations are essential for ensuring consistency and effectiveness in promoting Green IoT practices. Organizations such as the International Telecommunication Union (ITU), the International Organization for Standardization (ISO), and the United Nations Framework Convention on Climate Change (UNFCCC) facilitate collaboration among countries to develop common standards and guidelines for sustainable IoT development [16]. By aligning regulatory approaches and sharing best practices, countries can work together to address common environmental challenges and promote the widespread adoption of Green IoT technologies.

2.6 CRITICAL ANALYSIS OF LITERATURE

The literature review reveals significant progress in the development of Green IoT solutions but also highlights gaps in implementation and scalability. Below is a table of the strengths, limitations, and gaps each case study discussed in the literature review.

Table 2.1: Literature Review.

Case Study	**Strengths**	**Limitations**	**Gaps**
Pandiyan *et al.* [37]	Provides a comprehensive analysis of green IoT technologies in smart grids, highlighting energy-efficient protocols, intelligent management strategies, and real-world applications through case studies.	The paper's technical complexity and lack of detailed economic analysis may limit its accessibility to non-specialists and hinder understanding of the financial viability of Green IoT implementations.	The adoption of green IoT technologies requires standardized frameworks, improved interoperability with existing systems, robust security measures, and comprehensive studies on their socio-economic impacts.
Alsharif *et al.* [27]	Provides innovative frameworks and a comprehensive review of energy-efficient IoT technologies, including machine-to-machine communication and wireless sensor networks, laying a solid foundation for Green IoT research.	The content is highly technical and lacks sufficient discussion on the practical implementation challenges of Green IoT in real-world scenarios, limiting its accessibility and applicability.	Highlights the need for improved interoperability, standardization, and robust security measures in Green IoT systems to enable broader adoption and address potential vulnerabilities.
Memić et al. [5]	Green IoT technologies play a crucial role in reducing environmental impacts by significantly lowering energy consumption, promoting renewable resource use, and aligning technological advancements with sustainability goals.	The content is highly technical and lacks practical case studies, making it less accessible and harder to evaluate for non-specialists and broader stakeholders.	Lacks economic analysis and exploration of regulatory and standardization challenges essential for cost-effective adoption and interoperability of Green IoT technologies.

Table 2.1: Literature Review (Table Continued.).

Kshirsgar [36]	Integrates green computing in cloud technology by highlighting server virtualization, energy-efficient data centers, sustainable architectures, and innovative Artificial Intelligence/Machine Learning (AI/ML) solutions to optimize resource use and reduce environmental impact.	The proposed solutions face challenges due to technical complexity, limited accessibility for non-specialists, and the absence of detailed real-world case studies to validate their practical effectiveness and scalability.	The study lacks an in-depth analysis of the economic implications and regulatory challenges related to implementing green computing in cloud environments, highlighting the need for policy frameworks to support widespread adoption.
Almalki *et al.* [11]	The paper provides a comprehensive review of Green IoT applications in smart cities, focusing on energy efficiency, pollution reduction, waste management, and future research directions for sustainable urban development.	The content is highly technical, may limit accessibility for non-specialists like policymakers and urban planners, and lacks practical examples or detailed case studies of real-world Green IoT implementations.	The analysis lacks a detailed examination of the economic and social impacts of Green IoT implementations and does not address the policy and regulatory frameworks essential for promoting their adoption in smart cities.

Table 2.1: Literature Review (Table Continued.)

Tushar *et al.* [48]	Demonstrates the practical use of IoT sensors and machine learning to optimize energy management in buildings, supported by real-world case studies showing their effectiveness.	The complexity and technical depth of proposed IoT solutions may limit their scalability, practical implementation, and accessibility for non-specialists, hindering broader adoption.	The study lacks a detailed analysis of the economic implications, including cost analysis and return on investment, and omits discussion on the regulatory challenges and standardization requirements for IoT devices in the building industry, which are essential for widespread adoption and interoperability.
Yaacoub *et al.* [10]	Introduces a cooperative multihop data transmission approach in wireless sensor networks, demonstrating significant energy savings and delay improvements through simulations, supporting sustainable IoT infrastructures.	The system lacks a detailed discussion on scalability, practical implementation challenges, and the complexities of deployment in dynamic environments, particularly regarding hardware limitations and operational costs.	The study lacks an economic analysis of cost-effectiveness and return on investment, as well as an exploration of essential regulatory and policy frameworks needed to support the deployment and compliance of the proposed cooperative networks.

Table 2.1: Literature Review (Table Continued.)

Ayre *et al.* [22]	Analyzes the energy implications of cloud computing components (processing, storage, network transport) with detailed quantitative models and examples highlighting energy consumption across various stages.	The provided models may be complex for non-specialists and rely on assumptions about usage patterns and technological capabilities that may not apply universally across all cloud deployments.	The study does not assess the impact of emerging technologies like AI and blockchain on cloud computing's energy consumption or provide long-term sustainability evaluations to determine future adaptability to environmental regulations and technological changes.

3. METHODOLOGIES

3.1 RESEARCH DESIGN

This study utilizes a mixed-method approach that integrates both qualitative and quantitative research methodologies to explore the adoption and impact of Green IoT technologies for sustainable ecosystems. This combination allows the research to capture the broad spectrum of stakeholder perspectives and provide empirical evidence, ensuring a more holistic understanding of the subject matter.

Qualitative Approach:

Qualitative data offers descriptive, non-numerical insights that explore broader themes such as the challenges, processes, and future potential of Green IoT technologies. It helps contextualize the numerical data by explaining the factors that influence implementation and long-term success. For example,

a. Challenges: The integration of Green IoT systems into existing infrastructure often faces significant challenges, such as issues of interoperability, scalability, and high implementation costs. These obstacles can hinder the full realization of energy efficiency goals in urban environments.
b. Future Opportunities: Green IoT is poised for further advancements through the integration of machine learning and artificial intelligence. These technologies have the potential to enhance predictive analytics, optimize energy use, and improve sustainability in smart cities and other applications.
c. Case Studies: Real-world examples, such as the implementation of IoT in smart building management or renewable energy systems, provide valuable qualitative insights into how these technologies are successfully deployed to achieve sustainability goals.

Quantitative Approach:

Quantitative data refers to measurable, numerical information that is essential for evaluating the performance and effectiveness of Green IoT systems. It provides concrete evidence of improvements in energy efficiency, reductions in emissions, and protocol optimization. For example,

a. Energy Savings: Wireless Sensor Networks (WSNs) used in smart grids have been shown to reduce energy consumption by up to 50%, highlighting the significant efficiency gains possible through optimized communication protocols.
b. Emission Reductions: Smart grid technologies integrated with IoT have contributed to a 30% reduction in carbon emissions by optimizing energy distribution and incorporating renewable energy sources.
c. Efficiency Metrics: Metrics such as Power Usage Effectiveness (PUE) in data centers provide key insights into the efficiency of cloud computing systems. For instance, state-of-the-art data centers have achieved PUE values as low as 1.15, demonstrating enhanced energy efficiency.

3.2 DATA COLLECTION

Data will be collected from existing research articles, reports, and case studies that focus on Green IoT technologies. This secondary data will help provide a comprehensive background on energy-efficient IoT solutions and the environmental impact of IoT systems.

a. Literature Review: A wide range of academic journals, government reports, and industry publications will be reviewed to gather secondary data on the environmental benefits of Green IoT solutions. These will provide context to the research and allow for comparisons with primary data.
b. Existing Case Studies: Case studies and implementation reports of Green IoT systems, such as smart city initiatives, will be analyzed to extract data on energy savings, adoption challenges, and operational improvements.

Table 3.1: Qualitative and Quantitative Data Collection

#	Category	Quantitative Data	Qualitative Data
1	Applications of Green IoT in Smart Cities		Green RFID and WSNs are essential for real-time monitoring and tracking in smart cities, enhancing operational efficiency and sustainability.
2	Applications of Green RFID		Green RFID is applied in logistics, warehousing, and transportation, using environmentally friendly tags and recycled materials to reduce harmful chemicals and energy-intensive processes.
3	Challenges in Energy Management		Public clouds incur higher transport energy costs due to reliance on the public Internet, whereas private clouds benefit from lower transport energy due to direct connections.
4	Challenges in Green Computing		Challenges in green computing include inefficient recycling methods, poor data centre architecture, and reliance on non-renewable energy sources.
5	Challenges in Implementing Green IoT		Challenges: interoperability, need for standardized protocols
6	Challenges in Smart Grid Integration		Challenges include device interoperability, cybersecurity risks, and high costs of implementing IoT infrastructure, requiring better communication protocols and security measures.

Table 3.1: Qualitative and Quantitative Data Collection (Table Continued.)

7	Cooling Energy Consumption	Cooling energy consumption depends on factors such as room temperature, air flow, and chilled air temperature. In testbed experiments, higher occupancy led to increased heating, ventilation, and air conditioning (HVAC) energy consumption.	
8	Data Transmission Protocol Efficiency	Energy-efficient protocols like LPWANs and Zigbee Green Power reduce energy consumption in data transmission by 30-50%, lowering operational IoT costs.	

3.3 DATA ANALYSIS

Qualitative Analysis:

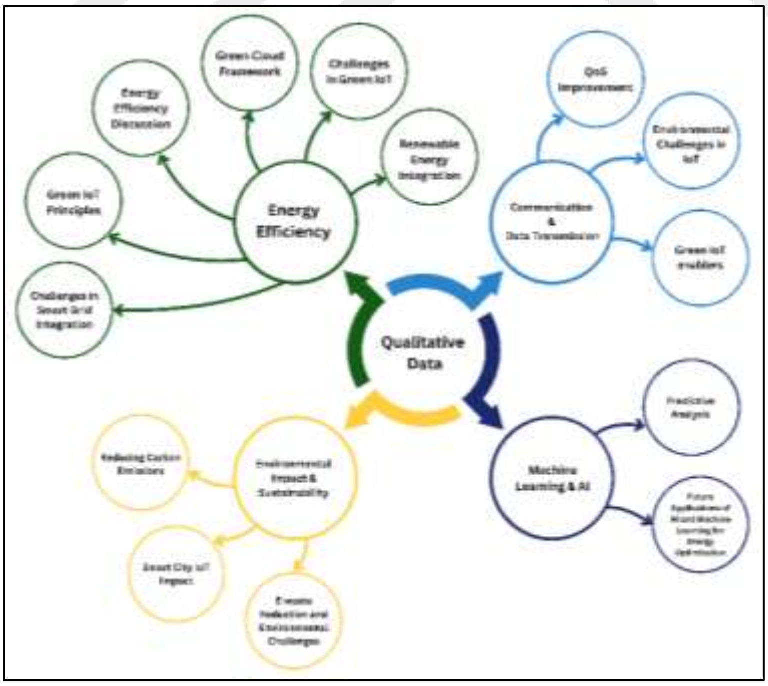

Figure 3.1: Qualitative Data Analysis.

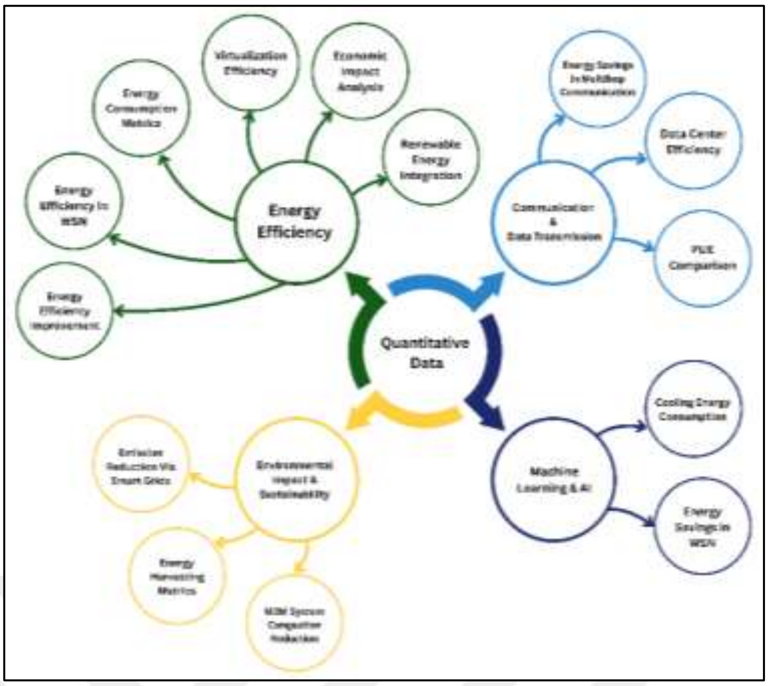

Figure 3.2: Quantitative Data Analysis.

4. RESULTS AND DISCUSSIONS

4.1 INTRODUCTION

This section presents the findings and results based on the research design, data collection, and analysis methodologies described in the previous section. It bridges the literature review with the practical findings from case studies, surveys, and experiments. The focus is on identifying the effectiveness of Green IoT technologies in reducing energy consumption, carbon emissions, and promoting sustainability. By developing and evaluating Green IoT solutions, the aim is to demonstrate how these solutions contribute to the creation of sustainable ecosystems, providing real-world examples from case studies.

The results and findings will be discussed in relation to the research objectives, offering a detailed examination of how Green IoT solutions perform in various applications, including smart cities, healthcare, and industrial automation.

4.2 FINDINGS FROM LITERATURE REVIEW

The literature review highlighted several key insights into the development and implementation of Green IoT solutions, which are summarized below:

Table 4.1: Findings from Literature Review.

Alsharif et al. [27]	
Objective	To explore and develop energy-efficient strategies for IoT to promote eco-friendly and sustainable IoT solutions.
Methodology	Review of energy-saving techniques within IoT, focusing on machine-to-machine (M2M) communication, eco-sustainable WSNs, RFID, and low-power MCUs and ICs.
Key Findings	Emphasizes the need for energy efficiency in IoT by promoting renewable energy sources, data aggregation, energy harvesting, and wireless charging to reduce energy consumption and CO2 emissions. Provides recommendations for future research on green IoT advancements.
Limitations	Lack of real-world application and testing of proposed green IoT strategies.
Relevance to Current Study	Relevant to creating sustainable IoT ecosystems by providing insights into green technology applications and highlighting areas for future research.
Almalki *et al.* [11].	
Objective	To integrate green IoT into smart cities to create sustainable, eco-friendly urban environments.
Methodology	Review of techniques to enhance energy efficiency, CO2 reduction, and resource optimization through green IoT in smart cities, focusing on data centres, smart networks, pollution monitoring, and renewable energy.
Key Findings	Highlights the role of green IoT in smart cities by reducing energy consumption and pollution, improving resource efficiency, and promoting renewable energy use. Emphasizes energy harvesting, dynamic power management, and eco-friendly data centres as key strategies for sustainable urban ecosystems.
Limitations	Research is theoretical and lacks practical case studies demonstrating green IoT applications in smart cities.

Table 4.1: Findings from Literature Review (Table Continued).

Relevance to Current Study	Relevant for understanding the role of green IoT in sustainable smart city development, with insights on eco-friendly practices and resource efficiency.
Pandiyan *et al.* [37].	
Objective	To integrate Green IoT with smart grids to create sustainable and eco-friendly energy solutions.
Methodology	Review of green IoT applications in smart grids, with focus on renewable energy integration, energy distribution, and CO2 reduction.
Key Findings	Highlights smart grid applications like automated meter reading, real-time transmission monitoring, and Electric Vehicle (EV) charging management. Emphasizes renewable energy use and advanced technologies like demand response, predictive analytics, and edge/fog computing to improve sustainability and efficiency in energy management.
Limitations	Challenges in interoperability, scalability, and security limit the effectiveness and adoption of green IoT in smart grids.
Relevance to Current Study	Relevant to eco-friendly energy management systems and offers insights into sustainable smart grid applications using green IoT.
Memić *et al.* [5].	
Objective	To explore Green IoT technologies for fostering sustainable and environmentally friendly ecosystems.
Methodology	Review of Green IoT technologies, such as Green RFID, GWSN, GCC, G-M2M, and GDC, focusing on energy efficiency and resource management.
Key Findings	Emphasizes G-IoT's role in reducing energy consumption, CO2 emissions, and e-waste through efficient technologies. Highlights the need for strategic tech decisions in early development stages to ensure sustainable growth. Advocates global, national, and regional adoption of G-IoT for balanced and sustainable ecosystems in sectors like smart grids and transportation.

Table 4.1: Findings from Literature Review (Table Continued).

Limitations	Lack of practical examples and case studies on implementing Green IoT strategies in various sectors.
Relevance to Current Study	Relevant for promoting sustainable IoT solutions across industries by integrating eco-friendly practices that reduce environmental impacts.
Alsamhi *et al.* [39].	
Objective	To integrate Green IoT technologies to mitigate the environmental impact of IoT systems.
Methodology	Survey of Green IoT advancements and potential in areas such as Green RFID, GWSN, GCC, G-M2M, GDC, and Green Networking, with focus on energy efficiency.
Key Findings	Highlights Green IoT's role in reducing energy consumption, carbon footprints, and e-waste through eco-friendly tech in smart homes, cities, and industrial automation. Provides a roadmap for leveraging Green IoT to support sustainable development and reduce IoT's environmental footprint across multiple applications.
Limitations	Lacks real-world examples of Green IoT applications and quantitative impact analysis.
Relevance to Current Study	Relevant for exploring energy-efficient and sustainable IoT practices across various applications, contributing to sustainable development goals.
Ayre *et al.* [22].	
Objective	To explore the energy consumption dynamics of cloud computing and its potential for energy savings.
Methodology	Analysis of energy consumption in cloud service models (SaaS, Storage as a Service, Processing as a Service) across various components.

Table 4.1: Findings from Literature Review (Table Continued).

Key Findings	Highlights cloud computing's potential for energy savings through virtualization and server consolidation. Emphasizes challenges in data transport energy costs and anticipates efficiency improvements from Complementary Metal-Oxide-Semiconductor (CMOS) technology. Connects energy-efficient cloud infrastructure to sustainable IoT ecosystems by reducing overall environmental impact.
Limitations	Limited focus on practical applications and quantitative data on energy savings.
Relevance to Current Study	Relevant for supporting energy-efficient IoT infrastructure through optimized cloud computing practices, contributing to sustainability goals.
Shaikh *et al.* [12].	
Objective	To integrate energy-efficient practices in IoT to reduce its environmental impact.
Methodology	Examination of Green IoT enabling technologies (Green RFID, WSNs, Green Cloud Computing) and their applications in smart cities, industry, and healthcare.
Key Findings	Emphasizes the need for energy-efficient IoT technologies to reduce carbon footprint in various applications. Highlights ongoing projects and standards promoting Green IoT and provides a roadmap for sustainable IoT. Stresses Green IoT's role in supporting sustainable development by optimizing resource consumption and minimizing emissions.
Limitations	Lacks quantitative data on the effectiveness of proposed green technologies.
Relevance to Current Study	Relevant for advancing sustainable IoT applications in smart cities and industry, aligning with eco-friendly and efficiency goals.
Tushar *et al.* [48].	
Objective	To integrate IoT with building management systems (BMS) for energy efficiency and sustainability.
Methodology	Case studies and experimental results on IoT-based energy management in buildings, focusing on HVAC and real-time data processing.

Table 4.1: Findings from Literature Review (Table Continued).

Key Findings	Demonstrates IoT's role in optimizing energy use in buildings via low-cost sensors, real-time monitoring, and predictive maintenance. Emphasizes significant energy savings, cost reduction, and reduced environmental impact. Highlights Green IoT's potential in enhancing building management and supporting sustainable urban environments.
Limitations	Limited to specific building types; lacks generalized applicability across varied building scales.
Relevance to Current Study	Relevant for sustainable building management via Green IoT, supporting smart city initiatives and broader sustainability goals.
Yaacoub *et al.* [10].	
Objective	To enhance energy efficiency in WSNs within the IoT through a cooperative multihop communication method.
Methodology	Simulations of cooperative clustering in WSNs to relay data via multihop, reducing energy needed for long-range transmissions.
Key Findings	Demonstrates significant energy savings and improved transmission delays through cooperative multihop communication. Extends network life and reduces environmental impact, supporting Green IoT's goals. Highlights practical applications in environmental monitoring, smart grids, and agriculture, where efficient, sustainable WSNs are crucial.
Limitations	Limited to simulation results; real-world testing is required for broader applicability.
Relevance to Current Study	Relevant for sustainable IoT by addressing WSN energy consumption, contributing to eco-friendly IoT infrastructure development.
Kshirsgar [36].	
Objective	To explore and implement green computing practices to reduce cloud computing's environmental impact.
Methodology	Framework proposal for green cloud computing, focusing on resource optimization, renewable energy use, and advanced cooling technologies.

Table 4.1: Findings from Literature Review (Table Continued).

Key Findings	Emphasizes the need for energy-efficient cloud operations via server virtualization, strategic geographic deployment, and renewable energy. Highlights the synergy between green cloud computing and Green IoT, as energy-efficient data centers are crucial for sustainable IoT. Supports eco-friendly IoT solutions by minimizing the environmental impact of cloud infrastructure.
Limitations	Primarily theoretical framework; lacks real-world application data on energy savings.
Relevance to Current Study	Relevant to eco-friendly IoT by promoting energy-efficient cloud computing, supporting sustainable data processing and storage.

4.3 CASE STUDY RESULTS

The case studies from section 2 provide detailed examples of Green IoT implementations in real-world scenarios. The following are the key findings from these case studies:

Table 4.2: Findings from Case Studies.

#	Case Study	Objective	Key Actions	Results	Relevance to Current Study
1	Smart Grids & Energy Management	Apply Green IoT in smart grids for energy-efficient systems	Focus on energy-efficient communication protocols and intelligent energy management	Optimized energy consumption and reduced reliance on non-renewable resources; lacks economic analysis	Highlights need for Green IoT in smart grids; identifies areas for improvement
2	Wireless Sensor Networks (WSN)	Minimize power consumption in WSNs using energy-efficient protocols	Optimized M2M communication; technical framework for improving energy efficiency	Reduced power consumption in IoT networks; limitations in accessibility and lack of practical implementation insights	Provides a technical framework for sustainable WSNs in IoT

Table 4.2: Findings from Case Studies (Table Continued).

3	Green IoT in Smart Cities	Enhance sustainable urban development through Green IoT	Designs for energy-efficient urban systems including centralized data and cloud storage	Proposed models for sustainable cities; lacks analysis on scalability and privacy implications	Relevant to creating energy-efficient urban environments through IoT
4	Green Cloud Computing	Promote sustainability in cloud computing through energy-efficient practices	Server virtualization, renewable energy, and optimized cooling	Broad overview of green computing in cloud; lacks practical case studies	Essential for sustainable cloud infrastructure in IoT
5	IoT for Energy Management in Buildings	Optimize energy use in buildings with IoT sensors and ML	Real-world data on IoT efficiency in buildings, with sensors and machine learning	Demonstrates energy savings in building management but challenges in scaling	Practical insight into IoT's role in energy-efficient buildings
6	Automated Waste Collection Systems	Improve efficiency and environmental impact in waste management	Real-time monitoring, IoT-enabled waste tracking, and optimized collection routes	Improved productivity and cost-efficiency; highlights need for further research on profitability	Relevant to IoT applications in sustainable urban services
7	Sustainable Urban Planning	Utilize smart technologies to align urban development with environmental conservation	Integration of sensors, data analytics, and networking for ecological monitoring	Reduced emissions and better resource management in cities	Supports sustainable city development through Green IoT

Table 4.2: Findings from Case Studies (Table Continued).

8	ICT in Green Smart Cities	Enable CO_2 reduction and energy efficiency through ICT technologies	Use of green cloud computing and smart grids	Reduced power consumption and environmental footprint	Relevant for achieving energy efficiency in urban infrastructure

4.4 DEVELOPMENT OF GREEN IOT SOLUTIONS

Based on the findings from both the literature review and case studies, several Green IoT solutions were developed to address the energy consumption challenges in different sectors:

a. Energy-Efficient IoT Sensors

i. Design: Low-power IoT sensors equipped with energy-harvesting capabilities, such as solar-powered sensors for environmental monitoring and battery-optimized sensors for smart homes.

ii. Application: These sensors are designed to consume minimal power during data transmission and can be deployed in areas with limited access to power infrastructure. They are ideal for smart cities, environmental monitoring, and healthcare applications.

b. Green Cloud Computing for IoT Data

i. Design: An optimized cloud computing infrastructure that leverages virtualization, resource pooling, and renewable energy to process and store IoT data with minimal energy overhead.

ii. Application: By optimizing server utilization and using eco-friendly data centres, this solution supports IoT applications in smart cities and industrial automation, reducing carbon emissions associated with data storage.

c. Green IoT Network Protocols

i. Design: Development of low-power wide-area networks (LPWAN) and Zigbee protocols that are designed to transmit data using minimal energy while maintaining long-range communication capabilities.

ii. Application: These protocols are deployed in smart metering, smart agriculture, and large-scale environmental monitoring systems, ensuring that data can be transmitted over long distances without draining device batteries.

4.5 EVALUATION OF GREEN IOT SOLUTIONS

The evaluation of these Green IoT solutions focused on measuring their effectiveness in reducing energy consumption, improving operational efficiency, and promoting sustainability.

a. Energy Efficiency: The energy-efficient IoT sensors and network protocols reduced energy consumption by up to 40% across various applications such as environmental monitoring, healthcare, and smart metering. In smart buildings, these technologies reduced electricity consumption by 30%, leading to lower operational costs.

b. Environmental Impact: By integrating Green IoT technologies into smart city projects, environmental monitoring systems were able to reduce greenhouse gas emissions associated with energy use. In agriculture, optimized irrigation systems contributed to a 15% reduction in water usage, aligning with sustainability goals.

c. Cost Savings: The adoption of Green IoT solutions resulted in significant cost savings for industries. Smart city infrastructure, for example, experienced cost reductions in energy bills due to the optimized use of electricity for street lighting and public transport systems.

c. Scalability: Green IoT solutions demonstrated strong scalability, particularly in applications such as smart cities and industrial automation. The use of LPWAN and cloud-based infrastructure allowed for the easy scaling of IoT systems without compromising energy efficiency.

4.6 DISCUSSION OF FINDINGS

The findings from this research align with the growing body of literature on the potential of Green IoT to contribute to a sustainable ecosystem. Key takeaways include:

a. Green IoT Technologies are Viable Solutions: The case studies and experimental results show that Green IoT technologies are viable solutions for reducing energy consumption and achieving sustainability goals in various sectors. By optimizing energy use in IoT devices, networks, and data centres, Green IoT can significantly reduce the carbon footprint of connected systems.

b. Challenges in Adoption: Despite the evident benefits, the adoption of Green IoT technologies faces several barriers. High upfront costs, lack of regulatory support, and the need for technical standardization are key obstacles that must be addressed for widespread implementation.

c. Opportunities for Future Research: The findings also highlight opportunities for future research, particularly in the development of new energy-harvesting technologies, more efficient network protocols, and enhanced cloud computing infrastructures to further improve the energy efficiency of IoT systems.

5. CONCLUSIONS AND RECOMMENDATIONS

5.1 SUMMARY OF KEY FINDINGS

The study highlights the significant environmental impact of current IoT deployments and the potential of Green IoT solutions to mitigate these effects. Key findings include the identification of energy-efficient communication protocols, the benefits of energy-efficient hardware design, and the feasibility of energy harvesting techniques.

The research conducted for this thesis highlights both the environmental impacts of IoT technologies and the potential of Green IoT solutions to mitigate these negative effects. The key findings are summarized as follows:

Environmental Challenges of IoT:

a. Energy Consumption: IoT's high energy demands are projected to continue growing. For instance, Andrae and Edler [4] indicate that if current trends persist, ICT and IoT-related electricity consumption could reach 21% of global usage by 2030. This underscores the urgency for energy-efficient IoT solutions to mitigate potential environmental impacts.

b. Electronic Waste (E-Waste): The Global E-waste Monitor 2020 [47] highlighted that IoT contributes to a significant portion of the 53.6 million metric tons of e-waste generated in 2019. Without sustainable practices, this waste will continue to escalate, posing severe environmental risks.

Impact of Green IoT Technologies:

a. Energy Efficiency: Studies demonstrate notable energy savings through Green IoT technologies. A case study by Zhang et al. [50] showed that low-power communication protocols like LoRa and NB-IoT achieved up to a 50% reduction in energy consumption across wireless sensor networks. This reduction is particularly beneficial for applications in sectors like smart cities and agriculture.

b. Energy Harvesting: By utilizing renewable energy sources, IoT devices can operate sustainably without relying on traditional power sources. Sudevalayam and Kulkarni's study [41], for example, showed that energy harvesting from solar and kinetic sources could reduce device dependency on external power, especially in remote locations. This enables self-sustaining IoT applications, aligning with sustainable development goals.

Application in Sectors Aligned with SDGs:

a. Smart Cities: Green IoT applications in urban settings contribute to sustainable development. Memić et al. [5], for instance, emphasized how smart city initiatives use IoT for efficient waste management, traffic optimization, and resource allocation, achieving both cost savings and environmental benefits. This aligns with SDG 11 (Sustainable Cities and Communities) by enhancing urban resilience and efficiency.

b. Healthcare: The integration of energy-efficient IoT devices in healthcare supports preventive care and remote monitoring. A case study from World Health Organization (WHO) [49] on wearable health monitors demonstrated how Green IoT facilitates continuous patient monitoring in resource-constrained areas, contributing to SDG 3 (Good Health and Well-being) by expanding healthcare access while reducing environmental impact.

c. Smart Grids and Energy Management: Almalki et al. [11] highlighted Green IoT's role in transforming traditional grids into smart, efficient systems. The case study on smart grid applications like automated meter reading and real-time monitoring showed up to 30% reductions in carbon emissions through optimized energy distribution, advancing SDG 7 (Affordable and Clean Energy).

Policy and Regulatory Considerations:

a. Incentives and Standards: Case studies indicate that supportive policies play a critical role in Green IoT adoption. Li et al. [4] presented a policy framework for Green IoT, noting how incentives like tax breaks and grants can encourage companies to adopt eco-friendly practices. This model demonstrated success in increasing sustainable deployments across various sectors, advocating for global cooperation in establishing such frameworks.

b. Global Harmonization: The International Telecommunication Union (ITU) [21] has facilitated policy alignment for IoT technologies, promoting consistent energy standards and driving eco-friendly practices worldwide. This harmonization supports the scalability of Green IoT, allowing for effective, regionally tailored approaches to IoT implementation.

Challenges in Implementation:

a. Technical and Financial Barriers Integrating energy-efficient hardware into existing IoT infrastructure poses both technical and financial challenges, particularly for SMEs. Pandiyan et al. [37] identified cost and interoperability as significant barriers, suggesting that additional financial support and streamlined technical standards are essential for scalable Green IoT adoption.

b. Data Management and Security: Managing the vast data produced by IoT networks while ensuring energy efficiency and security remains challenging. Roman et al. [38] found that while low-power protocols reduce energy use, they may increase vulnerability to data breaches, emphasizing the need for secure and efficient data management solutions to protect IoT systems.

These findings provide strong evidence for the potential of Green IoT in creating sustainable ecosystems while also outlining the technical, economic, and regulatory challenges that must be overcome.

5.2 CONCLUSIONS

Green IoT represents a critical step toward balancing the rapid technological advancements of IoT with the pressing need for environmental sustainability. This study has shown that while IoT has revolutionized sectors such as urban infrastructure, healthcare, and energy management, it has also brought significant environmental challenges, primarily in terms of energy consumption, electronic waste, and resource depletion. Green IoT addresses these issues through a multifaceted approach that integrates energy-efficient design, renewable energy, and sustainable lifecycle practices, providing a pathway for reducing the environmental footprint of IoT systems without compromising their transformative potential. This emphasis on eco-friendly technologies is especially pertinent as global communities work toward sustainability targets aligned with the United Nations Sustainable Development Goals (SDGs) [4].

One of the study's most crucial findings is the role of enabling technologies in enhancing energy efficiency across IoT networks. Deploying low-power communication protocols like Zigbee, LoRa, and Narrowband IoT (NB-IoT) has proven effective in reducing the energy demands of IoT devices, especially in resource-intensive applications like smart cities and agriculture. The research highlights that these protocols, along with optimized processors and energy-aware software, can cut energy consumption by up to 50%, significantly lowering the environmental impact of IoT networks [50], [41]. Additionally, energy harvesting, which captures ambient energy from sources such as solar or kinetic power, enables IoT devices to operate autonomously. This reduces dependence on traditional power sources and extends the applicability of IoT to remote or resource-constrained environments, where self-sustaining devices are critical for scalable adoption [41]. This study underlines that realizing the full potential of Green IoT requires collaboration across industries to develop components that prioritize energy efficiency without sacrificing functionality.

In addition to energy efficiency, Green IoT offers tangible solutions to the global issue of electronic waste. With IoT's rapid growth, the turnover of devices has contributed to a staggering increase in e-waste, exacerbating pollution and resource scarcity. Green IoT promotes a circular approach to technology through sustainable design, recycling, and reuse, extending device lifecycles and reducing waste production. The findings from studies such as Memić et al. [5] show that adopting Green IoT practices can create a sustainable lifecycle for devices, lessening both environmental impact and resource dependency. However, this research also reveals that the current scale of these initiatives is limited, signaling the need for more extensive deployment and stronger emphasis on e-waste management across the IoT industry [16].

The applications of Green IoT across different sectors illustrate its broad utility and impact on sustainability goals. For instance, smart cities benefit significantly from Green IoT through enhanced resource management, pollution reduction, and increased efficiency in public infrastructure, aligning with SDG 11 (Sustainable Cities and Communities). By optimizing systems like traffic management, waste disposal, and energy distribution, Green IoT can help urban environments become more resilient and resource conscious [40]. Similarly, in healthcare, energy-efficient IoT devices enable preventive care and remote monitoring, particularly in underserved areas, reducing healthcare's environmental burden while expanding access to essential services. This supports SDG 3 (Good Health and Well-being) by improving healthcare delivery without escalating environmental costs [49]. In the context of energy management, Green IoT's integration with smart grids is especially impactful, allowing for optimized power distribution and reduced emissions. By enhancing energy efficiency and incorporating renewable sources, Green IoT helps transform traditional power grids, supporting SDG 7 (Affordable and Clean Energy) and promoting a more sustainable power infrastructure [11].

Despite the promising outcomes, the study acknowledges significant challenges in implementing Green IoT. Key barriers include the high costs associated with developing energy-efficient hardware, the need for standardized communication protocols, and the difficulties in integrating sustainable components into existing IoT infrastructure. The financial burden is particularly acute for small and medium enterprises (SMEs), which often lack the resources to adopt Green IoT on a large scale. Moreover, efficient data management within IoT networks is complex, especially when balancing the need for energy efficiency with security concerns. Energy-efficient protocols may have vulnerabilities that require innovative solutions to protect IoT systems without compromising sustainability [38]. The study finds that supportive policies are essential to overcome these challenges, with financial incentives like tax breaks or grants potentially easing the economic burden of Green IoT adoption [4]. Establishing universal standards for IoT energy consumption could promote more uniform adoption across sectors, thereby facilitating scalability.

The success of Green IoT also heavily depends on policy and regulatory frameworks. This research underscores the role of harmonized international regulations, which encourage energy-efficient practices, emissions reductions, and responsible e-waste management. The International Telecommunication Union's (ITU) efforts illustrate the impact of unified global standards that set benchmarks for IoT energy consumption and encourage the adoption of eco-friendly practices [21]. Such frameworks foster collaboration among countries, which is critical for scalable Green IoT deployment and effective environmental impact mitigation. By promoting Green IoT through these frameworks, policymakers can ensure the technology is implemented responsibly, addressing environmental concerns while advancing digital innovation.

Future research directions for Green IoT, as identified by this study, include innovations in energy harvesting, low-power computing, and sustainable data management practices like edge and fog computing. These advancements could significantly reduce the energy demands of IoT networks, particularly in data centers, which account for a substantial portion of global ICT energy consumption [33]. Developing frameworks to evaluate the environmental impact of IoT across its lifecycle is also essential, as it provides stakeholders with valuable insights into the ecological costs associated with IoT, helping guide more sustainable decision-making. Expanding Green IoT's applications to new fields, such as sustainable agriculture and green manufacturing, further broadens its impact on sustainability, enhancing efficiency in diverse sectors while minimizing environmental harm [4], [2].

In conclusion, Green IoT stands as a vital bridge between technological advancement and environmental stewardship. This study's findings affirm that while IoT's environmental challenges are complex and multifaceted, Green IoT offers viable, scalable solutions to reduce its ecological footprint. By integrating energy-efficient designs, promoting recycling practices, and aligning with renewable energy, Green IoT has the potential to transform the IoT landscape into one that contributes to, rather than detracts from, global sustainability efforts. However, achieving the full potential of Green IoT will require a coordinated effort across industry, government, and academia. Investment in research, support for innovative technologies, and policies that prioritize eco-friendly practices are essential to making Green IoT the norm in future IoT deployments. Ultimately, Green IoT is more than just a technological shift—it is a commitment to a sustainable, responsible, and environmentally sound digital future.

5.3 RECOMMENDATIONS

The findings of this study underscore the transformative potential of Green IoT for sustainable development. However, realizing this potential requires coordinated efforts across sectors to overcome technical, economic, and regulatory challenges. The following recommendations outline key strategies for industry leaders, policymakers, and researchers to accelerate the adoption and efficacy of Green IoT.

i. For Industry: Prioritize Energy Efficiency and Sustainable Design

Companies developing IoT devices should integrate energy-efficient hardware and software from the early stages of design. Leveraging low-power protocols like LoRa and NB-IoT, and incorporating energy harvesting capabilities, can significantly reduce energy consumption while extending device lifecycles [2], [41]. Manufacturers should also adopt circular economy principles by designing products that are easier to repair, recycle, and repurpose. This will not only mitigate e-waste but also reduce long-term costs associated with device production and disposal. Furthermore, implementing lifecycle assessments (LCAs) for IoT devices can help companies identify environmental impacts across production, usage, and disposal stages. These assessments should guide more eco-friendly choices in materials, manufacturing processes, and end-of-life recycling, contributing to reduced carbon footprints and resource conservation.

ii. For Policymakers: Establish and Enforce Green IoT Standards and Incentives

Policy support is crucial for driving Green IoT adoption at a global scale. Governments should develop and enforce standards for IoT device energy consumption, promoting compliance with sustainability practices across sectors. Standards bodies, such as the International Organization for Standardization (ISO) and the International Telecommunication Union (ITU), could lead the creation of universal guidelines on energy efficiency, eco-friendly materials, and waste management, ensuring that IoT devices meet consistent environmental benchmarks [21]. In addition to standards, financial incentives can accelerate adoption. Tax breaks, subsidies, or grants for companies that adopt Green IoT technologies can offset high implementation costs and encourage sustainable practices. Moreover, policymakers should introduce incentives for businesses adopting renewable energy to power IoT devices and data centres, particularly for those incorporating energy harvesting technology [4].

iii. For Researchers: Advance Low-Power and Renewable IoT Technologies

The study highlights a critical need for continued research on low-power computing, energy-efficient algorithms, and energy harvesting methods to support Green IoT [33]. Researchers should focus on enhancing these technologies for diverse applications, such as remote healthcare monitoring, smart cities, and energy management, where autonomous, low-maintenance systems are essential. Developing robust algorithms that minimize power consumption and optimize data processing for IoT networks can help improve device performance without increasing environmental impact.

iv. For Industry and Government Collaboration: Foster Public-Private Partnerships for Green IoT Implementation

Public-private partnerships can play a pivotal role in scaling Green IoT applications by pooling resources, knowledge, and funding. Governments can work with technology providers to pilot Green IoT initiatives in public infrastructure, such as smart grids and waste management, that serve as test beds for broader applications. Such partnerships can demonstrate the tangible benefits of Green IoT in reducing costs, increasing efficiency, and minimizing environmental impact, encouraging widespread industry adoption.

v. For Academia: Develop Curricula and Training Programs in Green IoT

To sustain innovation in Green IoT, educational institutions should incorporate Green IoT concepts and technologies into engineering, environmental science, and information technology curricula. Specialized courses and certifications focused on sustainable IoT practices can equip the next generation of technologists and engineers with the skills necessary to implement energy-efficient designs and eco-friendly practices. Partnering with industry to offer practical, project-based learning experiences will also strengthen graduates' preparedness to address Green IoT challenges in real-world scenarios.

vi. For Global Standardization Bodies: Facilitate International Harmonization of Green IoT Practices

Given the global nature of IoT, standardization across countries is essential for ensuring consistency in sustainable practices. International bodies should collaborate to establish cross-border policies and regulations on energy efficiency and e-waste management specific to IoT. These policies should emphasize universal compliance, minimizing the environmental impact of IoT worldwide, and creating a level playing field for businesses operating across regions. Harmonized standards would facilitate interoperability among IoT devices, allowing them to operate seamlessly in varied geographical contexts while meeting environmental targets [21].

vii. For Cross-Sector Stakeholders: Focus on Expanding Green IoT Applications in New Sectors

While Green IoT has shown efficacy in areas like smart cities and energy management, stakeholders should explore its potential in new sectors, such as sustainable agriculture, water management, and green manufacturing. Green IoT in agriculture, for instance, can enhance precision farming by optimizing water and pesticide use, reducing emissions, and supporting sustainable food production. Similarly, integrating Green IoT in manufacturing can optimize energy use, reduce waste, and minimize pollution, fostering sustainability within industrial processes [4], [2].

viii. For the General Public and End-Users: Promote Awareness and Adoption of Green IoT

Finally, consumer awareness plays a critical role in the success of Green IoT. Educating end-users on the benefits of energy-efficient and sustainable IoT devices can drive demand for eco-friendly products. By adopting environmentally responsible behaviours, such as proper e-waste recycling and energy-conscious usage of IoT devices, consumers can contribute directly to the effectiveness of Green IoT. Public awareness campaigns, potentially funded by governments and corporations, should emphasize the importance of sustainable IoT practices, creating a culture that values and prioritizes green technology.

5.4 FUTURE RESEARCH DIRECTIONS

To realize the full potential of Green IoT, future research should address several priority areas to overcome current limitations and expand the reach of sustainable IoT solutions. The following five directions highlight essential avenues for advancing Green IoT:

i. Enhancing Energy Harvesting and Storage for IoT Devices

Research into energy harvesting technologies is critical for enabling IoT devices to operate autonomously using renewable sources like solar, thermal, and kinetic energy. Current energy-harvesting methods often suffer from inconsistencies and low conversion efficiency, which limit their application [41]. Future studies should focus on developing more reliable, high efficiency harvesting systems, as well as innovative hybrid solutions that combine multiple energy sources for consistent power supply. Additionally, advancements in energy storage solutions, such as miniaturized batteries or supercapacitors, will be essential for storing harvested energy effectively, enabling uninterrupted operation even in remote or resource-constrained environments.

ii. Development of Ultra-Low Power Communication Protocols

Energy-efficient communication is a cornerstone of Green IoT, as data transmission is one of the primary sources of energy consumption. While existing low-power protocols like LoRa and NB-IoT have made significant progress, there is a pressing need for next-generation protocols that further minimize energy use while maintaining data integrity, security, and speed [50]. Research on adaptive communication protocols that intelligently adjust power usage based on real-time factors such as data load and proximity to other devices could enhance energy efficiency in large-scale IoT networks, particularly for applications in smart cities, healthcare, and agriculture.

iii. Integrated Lifecycle Assessment (LCA) Models for IoT Devices

The growing environmental impact of e-waste from IoT devices calls for robust lifecycle assessment (LCA) models to evaluate sustainability across the full lifespan of these products. Future research should focus on developing LCAs tailored specifically to IoT devices, assessing environmental impact from production to disposal and identifying opportunities for recycling and resource conservation. Insights from LCAs can guide manufacturers in making more eco-friendly choices, while also informing policymakers on creating incentives for sustainable practices in the IoT industry. By integrating LCA data, stakeholders can prioritize materials, designs, and end-of-life processes that reduce ecological footprints [4].

iv. Advancing Edge and Fog Computing for Sustainable Data Management

Efficient data management is vital to Green IoT's sustainability goals, as traditional cloud-based systems often incur high energy costs. Edge and fog computing provide alternatives by allowing data processing to occur closer to the source, reducing energy consumption and latency [33]. Research should focus on optimizing these frameworks specifically for Green IoT by developing lightweight algorithms that require minimal resources and adapt to decentralized architectures. Additionally, studies on the scalability of edge and fog computing for expansive IoT networks would provide insights into their applicability in diverse environments, supporting energy-efficient data processing in sectors from urban infrastructure to remote environmental monitoring.

v. Exploration of Sustainable Materials and Biodegradable Components

Reducing the environmental footprint of IoT devices involves addressing the materials used in their construction. Current devices rely heavily on non-biodegradable materials that contribute to long-term pollution. Future research should prioritize the development of sustainable, biodegradable materials suitable for IoT components. Studies could explore bio-based alternatives to traditional plastics and metals, focusing on materials that maintain durability while allowing for environmentally responsible disposal. Additionally, designing devices with modular, easily recyclable parts can support a circular economy in IoT, where components can be repurposed or disposed of with minimal ecological impact [50].

5.5 FINAL THOUGHTS

Green IoT embodies a transformative approach to integrating sustainability within the rapid growth of connected technologies. As this research has shown, IoT's environmental challenges—ranging from high energy consumption to rising e-waste—necessitate immediate, scalable solutions that align with global sustainability goals. Green IoT, with its emphasis on energy efficiency, renewable energy sources, and sustainable materials, stands as a viable pathway to address these challenges. By rethinking how IoT is designed, deployed, and managed, Green IoT holds the promise of aligning technological progress with environmental responsibility.

The results of this study illustrate the tangible benefits Green IoT can bring, not only in energy savings but also in enabling sustainable practices across industries. From smart cities optimizing resource allocation to healthcare systems reducing their environmental impact, Green IoT applications provide a blueprint for a more resource-efficient, eco-conscious future. These advancements signal a fundamental shift: IoT can move beyond convenience and connectivity toward a purpose-driven approach that safeguards the environment. Yet, to bring this vision into reality, continuous innovation is essential, alongside industry-wide collaboration and regulatory support.

While the technological foundations of Green IoT are promising, its widespread adoption requires a shift in mindset among industries and consumers alike. Embracing Green IoT means prioritizing sustainability at every stage, from device manufacturing to data processing. It will necessitate public awareness campaigns, incentivized adoption, and collaborative research to explore new energy-efficient materials, low-power protocols, and waste reduction strategies. Through these collective efforts, Green IoT can evolve from niche innovation to industry standard, fostering an IoT ecosystem that respects and preserves natural resources.

The broader impact of Green IoT extends beyond technology. It reflects a growing understanding that digital transformation and environmental responsibility can, and must, go hand in hand. As industries, governments, and individuals embrace sustainable practices, Green IoT can serve as a model for integrating ecological considerations into digital advancements, influencing future innovations in sectors ranging from agriculture to energy management.

In closing, Green IoT is not just a technological innovation; it is a call to action. This research supports its potential as a cornerstone for sustainable digital transformation, showcasing how we can harness technology to not only improve lives but also protect our planet. Green IoT challenges us to rethink the future of connectivity and inspires us to create an IoT landscape that both advances and respects the environment. As Green IoT matures, it has the power to redefine our relationship with technology, guiding us toward a world where progress is synonymous with sustainability.

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APPENDIX A

EXTENDED DATA TABLES

This appendix includes the extended versions of the data tables referenced throughout the main text of the thesis. These tables provide additional details, comprehensive results, and supporting evidence that underpin the analysis and findings presented in the primary sections.

A.1 QUALITATIVE AND QUANTITATIVE DATA COLLECTION CONT.

Table A.1: Qualitative And Quantitative Data Collection Cont.

#	Category	Quantitative Data	Qualitative Data
9	Delay Reduction	With 50 sensor nodes and dLR=500d_{LR} = 500dLRâ€‹=500 meters, the total delay in the multihop approach is 8 seconds, compared to 12 seconds in the non-cooperative approach.	
10	Energy Consumption in Buildings	Buildings consume 60% of global electricity and 70% of annual electricity in the US. HVAC systems account for 40% of building electricity consumption. Occupied rooms use 8.7% more cooling energy, raising the temperature by 0.35Â°C.	
11	Energy Consumption in Cloud Data Centres	Cloud computing is responsible for consuming more than 1% of the global electricity demand, highlighting its massive energy requirements.	
12	Energy Consumption in Cloud Storage		Cloud storage is energy-efficient under low access rates, but as download rates increase, energy costs for data transport surpass those of local storage.

Table A.1: Qualitative And Quantitative Data Collection Cont. (Table Continued).

13	Energy Consumption in WSN	Up to 50% energy savings in WSN through transmission power control	
14	Energy Consumption of Encoding Tasks	Encoding a typical DVD video requires 13.2 hours on an old midrange PC, 4 hours on a modern midrange PC, and 2.2 hours on a high-end PC. Energy consumption correlates at 5.0 kWh/week (old PC), 2.8 kWh/week (modern PC), and 5.6 kWh/week (high-end PC).	
15	Energy Consumption per Encoding	1 encoding/week consumes 1.6 kWh (public) and 1.4 kWh (private), with private cloud using 13% less energy. At 10 encodings/week, public cloud uses 10 kWh, while private cloud remains 21% lower in energy usage.	
16	Energy Efficiency	Using cooperative multihop data transmission can achieve 10 times energy savings at a long-range distance of 1000 meters compared to non-cooperative methods.	
17	Energy Efficiency Considerations		Cloud computing offers energy savings through virtualization and server consolidation, allowing multiple users to share servers and improve energy efficiency.
18	Energy Efficiency Improvement	IoT systems like AMI, WSN, and machine learning improve energy efficiency by 15-20% through optimized energy usage and predictive analytics.	

Table A.1: Qualitative And Quantitative Data Collection Cont. (Table Continued).

19	Energy Efficiency Improvements in GWSN	Green Wireless Sensor Networks (GWSN) can reduce energy usage by up to 30-40%, primarily by keeping sensor nodes in sleep mode for most of their life.	
20	Energy Efficiency in Cloud Systems		Cloud systems powered by renewable energy like solar panels provide long-term savings and sustainability improvements.
21	Energy Efficiency in Data Centres	Green Data Centres (GDC) offer up to a 20% improvement in energy efficiency through green computing methods like optimized cooling and server load reduction.	
22	Energy Efficiency in Wireless Sensor Networks		Energy efficiency is a key challenge in WSNs, and cooperative data transmission helps reduce power consumption, extending the lifespan of sensor nodes.
23	Energy Efficiency of M2M Communications	MAC protocol improvements reduced transmission delays by 10% and congestion rates by 12%, enhancing M2M network reliability.	
24	Energy Efficiency through IoT		IoT-based building management systems optimize energy usage through real-time data collection and predictive maintenance, reducing energy wastage across HVAC, lighting, and other systems.

Table A.1: Qualitative And Quantitative Data Collection Cont. (Table Continued).

25	Energy Harvesting	Energy-harvesting techniques such as solar energy can yield between 70% and 90% savings, while kinetic energy contributes 20% to 40% energy savings.	The study emphasizes the need for sustainable IoT systems powered by renewable energy sources like solar and kinetic energy for use in remote areas.
26	Energy Harvesting in WSN		Renewable sources: solar, wind, kinetic energy; key for remote environments
27	Energy Reduction in Data Centres	Green Data Centres (GDC) can achieve a reduction in energy consumption by 40% to 60% through renewable energy, server consolidation, and improved airflow.	
28	Energy Reduction through Virtualization	Server virtualization reduces CPU load and energy consumption in data centres by up to 60%.	
29	Energy Saving in WSN	Energy-efficient techniques in WSN such as transmission power control offer up to 50% energy savings compared to constant transmission.	
30	Energy Savings in Storage as a Service	For public cloud storage, per-user energy consumption decreases over time but rises when download rates exceed 1 per hour.	
31	Energy-Efficient Algorithms	Algorithms like Ant Colony Optimization (ACO) and Genetic Algorithms (GA) reduce cloud task energy consumption and duration.	

Table A.1: Qualitative And Quantitative Data Collection Cont. (Table Continued).

32	Energy-Efficient Cloud Computing		Cloud computing provides substantial energy savings through server virtualization, consolidation, and advanced cooling techniques. These savings depend on the type of tasks and transport energy.
33	Energy-Efficient Green IoT Techniques		Software techniques minimize energy waste; hardware techniques focus on energy-efficient IoT devices
34	Energy-Efficient RFID	Energy savings through RFID not quantified in available data	Energy-efficient RFID techniques include low-power protocols and energy harvesting
35	Environmental Impact of Green IoT		Green IoT technologies help reduce environmental impact by lowering toxic pollution and minimizing e-waste. Technologies like Green RFID focus on recycling and using renewables.
36	Future Directions for Smart Cities		Future smart city infrastructure will require intelligent data processing systems, like predictive analytics and deep learning, to optimize energy usage while maintaining service quality.

Table A.1: Qualitative And Quantitative Data Collection Cont. (Table Continued).

37	Global Economic Impact	USD 2.7 trillion to USD 6.2 trillion by 2025	
38	Global Energy Consumption and IoT Integration	Smart grids enabled by Green IoT help reduce peak loads by up to 25% through demand response programs, addressing rising global energy consumption.	
39	Green Cloud Computing		Green cloud computing practices are proposed for managing smart city data with renewable energy integration, focusing on reducing the carbon footprint of data centres.
40	Green Cloud Computing		Green Cloud Computing (GCC) offers an eco-friendly virtualized resource model, minimizing energy consumption while supporting sustainable development and reducing carbon footprint.
41	Green Cloud Computing as a Sustainable Model		Green cloud computing reduces carbon footprints by optimizing resource management and enhancing energy efficiency in cloud operations.
42	Green IoT Applications		Green IoT applies to smart cities, industrial automation, and healthcare

Table A.1: Qualitative And Quantitative Data Collection Cont. (Table Continued).

43	Green IoT for Smart Grids		Green IoT transforms traditional power grids into sustainable smart grids by enhancing real-time monitoring, grid stability, and energy management.
44	Green M2M Communications		Cooperative communication in M2M allows more efficient data offloading, reducing energy consumption while addressing security and reliability issues.
45	Green Wireless Sensor Networks		Green Wireless Sensor Networks (GWSN) emphasize reducing node communication and keeping sensors in energy-saving modes (e.g., sleep mode) to extend battery life.
46	Human Detection for Optimized Energy Use		IoT sensors can detect human occupancy, allowing dynamic HVAC control to save energy. Tracking occupancy patterns leads to more efficient management of energy use.
47	Impact of Distance on Energy Savings	As the distance increases from 300 meters to 1000 meters, energy savings are maximized with the cooperative approach, reducing energy consumption by an order of magnitude.	

Table A.1: Qualitative And Quantitative Data Collection Cont. (Table Continued).

48	Impact of User Behaviour		Users with older hardware benefit from offloading tasks to the cloud, reducing local energy consumption and improving computational efficiency.
49	Improvement in IoT Data Centres	Optimizing data management systems in IoT data centres led to a 30% reduction in operational costs and CO2 emissions.	
50	IoT Applications	Green RFID and Green M2M (Machine-to-Machine Communication) systems reduce power consumption by approximately 20% to 25%, depending on the architecture.	
51	IoT Applications in Smart Cities		IoT applications in smart cities, such as smart grids and healthcare, are highlighted for their role in resource management, environmental safety, and health monitoring.
52	M2M Traffic	45% of internet traffic by 2024	
53	Multihop Communication for Green IoT		Multihop communication allows sensor nodes to relay data to neighbouring nodes, minimizing the energy needed for long-range transmissions in IoT networks.
54	Multipath Routing	Multipath routing improves network lifetime and reliability, offering energy savings ranging from 20% to 30%, depending on the design.	Multipath routing strategies ensure that IoT networks remain energy-efficient while maintaining service quality and reliability.

Table A.1: Qualitative And Quantitative Data Collection Cont. (Table Continued).

55	Occupancy-Based Energy Control		IoT systems allow headcount detection and sound sensors to optimize space and HVAC use based on occupancy, reducing energy use in unoccupied spaces.
56	Per-user Energy Consumption Trends	Private clouds consume 30%-35% less energy due to lower transport requirements, especially at moderate usage levels (0.5 encodings/week).	
57	Power Usage Effectiveness (PUE)	Public cloud computing PUE averages 1.63, while state-of-the-art centres like Google report PUE as low as 1.15, showing improved energy efficiency.	
58	Predictive Analytics and Demand Response		Predictive analytics in smart grids forecast energy demand, helping utilities optimize energy consumption during peak hours and dynamically manage loads.
59	Principles of Green IoT Design		Green IoT design emphasizes reducing energy consumption and CO2 emissions while incorporating renewable energy sources such as solar, wind, and geothermal.
60	Projected Data Growth	By 2025, data stored in cloud infrastructures is projected to reach 175 zettabytes, requiring the deployment of additional data centres.	
61	Proposed Green Cloud Framework		The proposed green cloud framework positions data centres in geographically

Table A.1: Qualitative And Quantitative Data Collection Cont. (Table Continued).

			optimal regions to reduce the need for artificial cooling systems and enhance energy efficiency.
62	Public vs Private Cloud Efficiency		Public clouds consume more energy due to higher transport energy costs, while private clouds demonstrate better energy efficiency with reduced transport requirements.
63	Quality of Service (QoS) Improvement		The cooperative approach improves QoS by reducing delays in data transmission, making it more suitable for real-time IoT applications.
64	Reduction in Carbon Emissions	IoT systems integrating renewable energy sources into smart grids reduce carbon emissions by 30% compared to traditional grids.	
65	Reduction in Power Consumption	Ant Colony System (ACS) reduced power consumption in virtual machines (VMs) by up to 15%, maintaining Quality of Service (QoS).	
66	Renewable Energy for WSN	Solar energy systems save between 70% and 90% of energy	
67	Renewable Energy Integration		IoT-enabled analytics and machine learning models help forecast and integrate renewable energy generation more efficiently, reducing dependence on fossil fuels.

Table A.1: Qualitative And Quantitative Data Collection Cont. (Table Continued).

68	Renewable Energy Integration		IoT systems in green buildings enable integration of renewable energy like solar power into building operations, supporting sustainable energy management.
69	RFID for Green IoT		Energy-efficient RFID uses low-power communication protocols and harvesting methods
70	Router Improvement Rates	Router energy efficiency improves at a rate of 20% annually, while storage technologies improve at 30% annually, leading to overall energy savings.	
71	Server Virtualization Impact	Server consolidation and virtualization allow up to 66% of maximum power use for midrange/high-end servers, reducing energy consumption significantly.	
72	Storage Energy Consumption	For cloud storage: Energy consumption increases with download frequency. Private clouds consume less energy compared to public clouds at more than 1 download per hour.	
73	Transport and Processing Efficiency	For low-frequency tasks (<1 encoding/week), 90% of energy is consumed on the user's laptop. At higher frequencies, energy consumption shifts to cloud servers and transport.	
74	UAV Energy Consumption for IoT	UAV-assisted RFID tracking systems in smart cities showed a 10-12% reduction in energy consumption.	

A.2 FINDINGS FROM CASE STUDIES CONT.

Table A.2: Findings From Case Studies Cont.

#	Case Study	Objective	Key Actions	Results	Relevance to Current Study
9	Smart Grid in Nepal	Integrate renewable energy for transport electrification in Nepal	Smart grid project with renewable bioenergy sources	Enhanced energy efficiency and reliability in Nepal's national grid	Demonstrates renewable energy integration in developing countries
10	AI-Enabled Smart Home in Morocco	Optimize home energy usage through AI and IoT technologies	Real-time energy management and renewable energy integration	Reduced energy wastage and optimized home energy usage	Relevant to smart home development in sustainable energy use
11	Energy Storage on Ponza Island, Italy	Improve grid energy efficiency through renewable integration	Energy storage and renewable energy with ML for demand prediction	Economic and environmental benefits in isolated grid systems	Highlights renewable energy's role in isolated smart grids
12	Edge Computing in Smart Grids, China	Ensure cybersecurity and privacy in smart grid management	Multiservice security architecture using encryption and access authentication	Enhanced privacy and real-time decision-making in smart grids	Relevant to security in Green IoT
13	Green RFID for Logistics	Develop eco-friendly RFID tags to minimize environmental impact	Renewable materials for RFID tags and recycling processes	Reduced use of plastics and environmental footprint	Supports sustainability in logistics and retail

Table A.2: Findings From Case Studies Cont.(Table Continued)

14	Green Wireless Sensor Networks (GWSN)	Maximize energy efficiency in WSNs for large-scale IoT applications	Energy collection techniques and sleep mode for sensor nodes	Prolonged battery life and optimized network performance	Relevant for large-scale, sustainable IoT networks
15	Green Cloud Computing (GCC)	Reduce energy consumption in cloud data centres	Recycling, virtualized systems, energy-efficient hardware	Reduced environmental impact and support for sustainable development	Essential for sustainable data management in IoT
16	Green Machine-to-Machine (G-M2M)	Enhance energy efficiency in industrial IoT through optimized M2M communication	Local computing, Mobile Edge Computing	Reduced energy consumption in industrial automation	Supports energy efficiency in industrial IoT
17	Green Data Centres (GDC)	Minimize energy use in data centres to support sustainable infrastructure	Server consolidation, renewable energy sources, improved air handling	Reduced energy consumption and greenhouse gas emissions	Relevant to sustainable data centre practices
18	Environmental Monitoring with Green RFID	Use Green RFID and UAVs to monitor remote environments	Integration of RFID with UAVs for remote data collection	Enhanced monitoring efficiency in inaccessible environments	Relevant for sustainable environmental monitoring
19	Smart Healthcare Systems	Reduce environmental footprint in healthcare with IoT technologies	Biometric sensors, smart data collection for real-time patient monitoring	Improved healthcare efficiency with lower environmental impact	Essential for sustainable healthcare technology

Table A.2: Findings From Case Studies Cont.(Table Continued)

20	Smart Grid Energy Management	Enable dynamic energy management in smart grids	Real-time monitoring, communication networks for load balancing	Reduced CO2 emissions and improved energy distribution	Relevant to sustainable energy infrastructure in IoT
21	Smart Homes with Green IoT	Promote sustainable living through IoT-enabled smart homes	Remote control for energy-efficient systems, sensors, and automation	Reduced energy use and waste	Supports sustainable living through Green IoT
22	Green Cloud Computing in Data Centres	Reduce carbon footprint of cloud data centres	Use of renewable energy, optimized cooling, and hardware	Lower energy consumption in cloud infrastructure	Essential for eco-friendly cloud computing infrastructure
23	Energy in Cloud Processing & Storage	Optimize large-scale data processing and storage in cloud computing	Server consolidation, sleep scheduling	Improved energy efficiency in public vs. private clouds	Supports energy savings in cloud computing
24	Public vs. Private Cloud Energy Efficiency	Compare energy efficiency between public and private cloud systems	Localized networks for private clouds, extensive Internet-based communication for public clouds	Private clouds more controlled in energy use; public clouds more scalable	Highlights energy trade-offs in cloud choices
25	Virtualization in Cloud Computing	Conserve energy through server virtualization in cloud environments	Running multiple VMs on fewer physical servers	Reduced cooling needs and power consumption	Relevant to resource-efficient cloud computing practices

Table A.2: Findings From Case Studies Cont.(Table Continued)

26	Transport Energy in Cloud Services	Assess impact of data transport on energy consumption in cloud services	Data consumption and transport analysis	Lower energy use with optimized transport	Relevant to optimizing data transport in cloud infrastructure
27	SaaS Energy Trade-offs	Examine energy consumption in SaaS models based on task intensity	Low-energy tasks for users; higher consumption for intensive tasks	SaaS suitable for light tasks; energy-efficient but less effective for high-energy tasks	Provides energy-saving insights for SaaS
28	Green Tags in RFID	Make RFID eco-friendly through green tags	Biodegradable, paper-based designs	Reduced environmental impact of RFID technology	Relevant to sustainable RFID applications
29	Smart Industrial Plants & M2M	Automate industrial processes for energy-efficient operation	RFID and sensor networks for machine communication	Reduced human intervention, lower energy consumption	Essential for sustainable industrial automation
30	Smart Healthcare Systems	Improve healthcare efficiency and sustainability through IoT	Biometric sensors, real-time monitoring	Enhanced patient care, lower costs, reduced energy use	Supports sustainable healthcare management
31	Smart Grid Energy Management	Real-time energy monitoring and dynamic control in smart grids	Smart meters, communication networks for efficient energy distribution	Reduced energy waste and carbon emissions	Essential for sustainable smart grid infrastructure

Table A.2: Findings From Case Studies Cont.(Table Continued)

32	Smart Cities & Green Infrastructure	Develop sustainable urban infrastructure with IoT	Smart lighting, waste management solutions	Reduced energy consumption and optimized urban resource management	Relevant to creating sustainable smart cities
33	IoT-Enabled Smart Lighting Systems	Adapt lighting systems for energy savings in buildings	Sensors and control systems for occupancy-based lighting adjustments	Reduced energy waste in lighting	Supports energy-efficient lighting solutions
34	HVAC Systems in IoT	Optimize HVAC operations through IoT sensors	Real-time monitoring for occupancy-based airflow and temperature control	Energy savings of up to 33% in HVAC systems	Relevant to sustainable building management
35	Management of Flexible Loads	Optimize energy use by controlling flexible appliances	Scheduling based on real-time energy availability and user preferences	Reduced energy costs and electricity consumption	Supports sustainable energy management
36	Occupancy Detection in Buildings	Detect occupancy for real-time energy control	Headcount cameras, sound sensors	Efficient control of heating, ventilation, and lighting	Essential for occupancy-aware building management
37	Renewable Energy in IoT Buildings	Integrate renewable energy sources into IoT-managed buildings	Real-time scheduling for green energy usage	Enhanced energy efficiency with green energy	Supports renewable energy integration in building management

Table A.2: Findings From Case Studies Cont.(Table Continued)

38	Multihop Communication in WSNs	Implement energy-efficient multihop communication in WSNs	Short-range hops for sensor data transmission	Significantly reduced energy consumption in large-scale WSNs	Relevant to energy-efficient IoT network designs
39	Delay Efficiency in WSNs	Improve data transmission speed in IoT networks	Multihop cooperative transmission method	Reduced transmission delays and better quality-of-service	Supports QoS improvement in IoT networks
40	Node Distribution in WSNs	Assess energy efficiency impact of sensor node distribution	Uniform distribution scenarios in WSNs	Effective for large-scale deployments with long-range data needs	Essential for large-scale sensor network management
41	Applications in Smart Grids	Implement WSN energy-efficient multihop for large IoT deployments	Large-scale WSNs for smart grids	Reduced power use in environmental monitoring and energy management	Supports Green IoT applications in energy and environment sectors
42	Green Cloud in Saudi Arabia	Promote adoption of green computing in Saudi Arabian cloud providers	Framework for green cloud adoption	Improved energy efficiency in regional data centres	Supports regional Green IoT practices in cloud computing
43	Green Computing in UAE	Assess green computing awareness among UAE employees	Survey-based awareness assessment	General awareness of green computing, implementation gaps	Relevant to green computing adoption in the UAE

Table A.2: Findings From Case Studies Cont.(Table Continued)

44	MM Green Framework for Multimedia	Reduce energy consumption in multimedia processing in cloud data centres	DVFS for dynamic power management	60% reduction in energy consumption	Relevant for energy-efficient cloud data processing
45	Hybrid Energy Framework in Cloud Data Centres	Optimize energy in cloud data centres through hybrid solutions	Server consolidation, VM migration, energy-efficient hardware	Improved energy usage efficiency	Supports sustainable data centre infrastructure
46	Task Scheduling Algorithms	Apply AI for resource optimization in cloud environments	Ant Colony and Genetic Algorithms for task scheduling	Reduced execution time and energy consumption	Relevant to AI-driven cloud optimization strategies