Application and Prospect of Smart Home Based on Internet of Things in Circular Economy

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Abstract

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Abstract

This study explores the application and prospects of Internet of Things-based smart home systems in promoting energy efficiency, device longevity, and Circular Economy adoption. With increasing global emphasis on sustainable living, IoT has emerged as a key enabler of smart home automation, real-time energy management, and waste reduction. However, challenges such as cost, security concerns, and system interoperability continue to hinder widespread adoption.

Using a mixed-methods approach, this study gathered data from 30 smart home users through survey questionnaires and interviews. Descriptive statistics revealed that IoT-enabled automation is widely perceived as beneficial for energy efficiency, but its direct impact on Circular Economy adoption remains limited due to implementation challenges. Correlation analysis highlighted weak associations between energy efficiency, device longevity, and sustainability practices, suggesting that external factors influence IoT adoption more significantly. Regression analysis confirmed that cost and security concerns, while perceived as barriers, were not statistically significant predictors of smart home adoption.

Findings suggest that IoT-enabled smart homes can optimize resource use, extend appliance lifespan, and support sustainability goals, but achieving full-scale adoption requires improvements in affordability, security, and system compatibility. The study recommends financial incentives, enhanced cybersecurity measures, and standardized IoT frameworks to strengthen the role of smart home automation in the Circular Economy.

Ultimately, while IoT-based smart homes offer substantial sustainability benefits, overcoming technological, economic, and behavioral barriers is crucial for their long-term success and environmental impact. Future research should focus on scaling IoT adoption through policy support, user education, and advanced automation solutions.

Keywords

CE: Circular Economy
IoT: Internet of things
ICT: Information and communication technology

Pages 31 pages and appendices 2 pages

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1 Introduction

Smart homes have captured widespread interest because they show promise to upgrade residential energy efficiency while improving living conditions. Residents can smoothly unite multiple services and technological solutions through the modern development of information and communication technologies (ICTs) and energy solutions in houses. Marikyan et al. (2019; pg: 305) describe smart homes using this definition: “a residential environment with information and communication technologies that offers suitable functions for resident convenience combined with security systems and entertainment and provides comfort needs.” Advanced management systems form the foundation of smart home technology because they provide residents with effective ways to monitor and manage their indoor spaces.

Smart residential spaces designed with current ICT along with energy technology platforms enable future development of unprecedented applications and services according to Shapsough and Zualkernan (2019; pg:66). The advancement of small sensor-powered ubiquitous computing technologies now connects various objects across all locations and during any time period. The data collection function of these devices then interconnects users across a networked system so that users become linked nodes in an information-sharing framework built without traditional communication methods. The foundation of Internet of Things exists through the concept of interconnectedness. Residents participating in IoT-enabled environments can interact and work with multiple devices and smart-home services according to Neagu et al. (2017; pg.: 54). According to Wang et al. (2021; pg.: 29) the study of IoT systems focuses on wireless sensor networks while also examining security issues and privacy risks linked to IoT framework vulnerabilities. Research shows IoT technologies advance continuously as they grow in prominence throughout smart environments including residential homes and urban metropolitans.

1.1 Background

The Circular Economy (CE) attracts widespread interest from policymakers and governments who pursue sustainable alternatives through bio-based products and renewable processing technologies (Agrawal & Singh, 2020; pg.: 1464). The CE targets present-day linear resource-to-waste systems through its focus on reuse and remanufacturing together with recycling methods to tackle environmental deterioration from traditional economic systems (Ghisellini et al., 2016; pg. 13; Murray et al., 2017 pg. 12).

Through its decoupling approach the CE supports enhanced resource usage efficiency, renewable energy integration and environmental sustainability (Merli et al., 2018; pg. 704; Korhonen et al., 2018; pg. 547). Systemic adjustments across production and consumption systems need to incorporate innovation and data-sharing and foster collaboration to create circular material loops (Ford & Fisher, 2019 pg. 2; Ávila-Gutiérrez et al., 2019; pg. 2).

The Internet of Things (IoT) represents a main technological force behind circular economy advancement by allowing connected devices to optimize automation and data sharing for process optimization (Atzori et al., 2010; Mehl, 2018). This allows IoT system to monitor the product movements from life stages with the purpose to support circular business models and improve supply chain monitoring as well as empower smart resource usage choices (Ingemarsdotter et al., 2019; Esmaeilian et al., 2020). Amongst the challenges that the adoption of IoT technologies faced today are the gaps of availability for data and issues on system integration, growth limits (Fatimah et al., 2020). According to Miaoudakis et al. (2020) and Rane and Thakker (2019) the present barriers to adoption must be resolved in order to harness the sustainable development capabilities of the IoT.

1.2 Problem Statement

Internet of things technology integration into smart homes due to the increase in sustainable living standards and resource efficiency that advocates for the adoption of CE principles. Currently, smart home systems offer convenience through automation, however they did not explore potential ways to improve energy optimization as well as increase device life spans and resource recycling. Such systems, however, face multiple implementation costs barriers across a range of implementation costs, and data are not always compatible and safe. Moreover, the adoption barrier has also been the lack of agreed upon rules. Automation is given far greater importance as compared to efficiency and energy management with no fundamental need to put in place an overarching mechanism that combines Circular Economy practices and the IoT capabilities. To propel forward, sustainable and efficient smart home ecosystems need to be identified first and then those practices coupled with policy recommendations should be taken to bring practical solutions.

1.3 Objectives of the Study

Below are the research objectives:

1. Explore how IoT technologies can be utilized to enhance energy efficiency in smart home systems.

2. Investigate the potential of smart home systems to increase the lifespan of household devices and facilitate resource reuse and recycling.

3. Examine the obstacles to integrating IoT-enabled smart home systems with Circular Economy principles and propose effective optimization paths.

4. Develop a smart home system framework that aligns with Circular Economy principles while ensuring practical functionality and operability.

1.4 Research Questions

This study has following research questions:

Q1: How can IoT technologies optimize energy use in smart home systems?

Q2: What is the potential of smart home systems to extend the life of household devices and promote resource recycling?

Q3: What are the obstacles and optimization paths for combining smart home technologies with Circular Economy principles?

Q4: How can a smart home system framework be designed to align with Circular Economy principles while ensuring practical operability?

1.5 Significance of the Study

In this thesis, the Internet of Things (IoT) technologies implementation in smart homes for implementing Circular Economy principles towards sustainability is addressed. Energy efficiency is optimized, product lifecycles are extended and resource management practices are changed, all efforts that have been developed with innovative environmentally friendly solutions in the research. Fundamentally, this research lays ground work in identifying principles of alignment between CE principals and application of practical application recommendations and frameworks. The research findings assist as well develop sustainable smart home system development by contributing knowledge important to public officers too as to researchers and industries which aim to achieve technological excellence but without compromising environmental accountability.

1.6 Structure of the Thesis

Five chapters serve essential purposes for completing a comprehensive analysis of the research targets. Chapter 1: The introduction incorporates the study foundation through its background analysis and statements about the problem along with research questions and objectives. Chapter 2: The Literature Review section first analyzes existing research about IoT technologies and smart homes and then the Circular Economy principles before exploring knowledge gaps to define the study's theoretical foundation. Chapter 3: A detailed presentation of research design and data collection approaches and analytical methods appears in the Methodology section. Chapter 4: This chapter discusses to bring together the data analytical outcomes and their key findings with their research implications. The concluding Chapter 5 calculates a summary of research findings and provides future work actionable recommendations for weaknesses identified.

2 Literature Review

This review examines existing research about IoT technology applications in the smart home with reference to Circular Economy principles. The review focuses on important principles such as minimization of energy consumption and maximization of product longevity as well as resource reutilization and identifies knowledge voids in current research. This section presents an evaluation on difficulties that happen during the deployment of IoT enabled smart home system into CE boundaries. The theoretical framework of the future research is based on reviewing existing literature in this segment.

2.1 Internet of Things

The Internet of Things (IoT) expands Internet use beyond Human-to-Human (H2H) interactions which primarily consist of messaging and video calls and social networking.

Artificial Intelligence advancements have made Human-to-Machine (H2M) interaction possible leading to personalized machine-generated content delivery. Moore's law as a guideline enables miniaturized electronics to create smart devices which integrate automatically into the Internet through embedded computers. The central aspect of IoT centers on connecting physical devices to the online world through its core capability of M2M interaction. IoT applications extend from domestic spaces through industrial operations reaching national borders and global markets to fulfill the seamless connectivity predictions from years past (Weiser, 1999; pg: 5).

The digital transformation of manufacturing which Blunck and Werthmann, (2017; pg: 3) describes as Industry 4.0 includes intelligent robot's sensor systems and 3D printing elements. The 2011 German-launched platform produces a x with IT (Kang, et al., 2016, pg:8) through IoT to enable connectivity between employees' machines suppliers and customers. According to Vermesan and Friess, (2014) IoT represents a paradigm linking various objects such as RFID tags and sensors and actuators and mobile phones for the accomplishment of common goals (Atzori, et al., 2010). Real-time tracking from IoT becomes the fundamental source for our decision support system which functions through this concept (El-Haddadeh et al., 2019: pg : 2). Products using IoT modules or radio chips act as digital product passports which store vital lifecycle data suitable for both businesses and supply chains and end users. IoT adoption requires resolving connectivity issues that pose difficulties during supply chain implementation across the network (De Angelis et al., 2018) as well as spanning supply chains (Haddud, et al., 2017, pg: 5; Chen, et al., 2014: pg 2).

The solution provided by 5G consists of elevated data throughput combined with adjustable band width alongside reduced power utilization and minute response times which are vital for time-sensitive IoT operations (Schulz, et al., 2017: pg 1). The widespread connectivity capabilities of 5G technologies position the system as a fundamental infrastructure to implement future circular supply chains (CSC) for sensitive applications among other uses (You et al., 2019: pg : 3). Roblek et al., (2016: pg: 1) explain that products with embedded sensors which monitor real-time usage send data through IoT networks for better decision-making processes. The research on applying Industry 4.0 technologies to CSC remains minimal. Genovese et al. (2017, pg 3) applied hybrid life cycle assessment (LCA) to compare linear and circular production while their system did not include fully automated real-time DSS for tracking analysis. Manual data collection which characterizes traditional LCA models either in top-down or bottom-up approaches proves inadequate for analyzing complex products. The subsequent portion outlines how semantic-oriented DSS improves decision processes for CEBM.

2.2 Circular Economy

Research and professional communities worldwide have been studying the Circular Economy (CE) extensively throughout the last decade. It represents an economic framework aimed at conserving resources, closing energy and material loops, and fostering sustainable development at three levels: micro (individual businesses and consumers), meso (networks of economic agents), and macro (cities, regions, and governments) (Prieto-Sandoval et al., 2018; pg: 10). CE promotes cyclical systems and regeneration-focused procedures in industrial processes while urging new laws to replace the linear approach of limited-resource utilization (Luthra et al., 2021: pg :3).

Rooted in various concepts including cradle-to-cradle design and industrial ecology and regenerative development CE works to eliminate waste while protecting all material value in product lifecycles (Geissdoerfer et al., 2018: pg:3). CE first appeared in the early 1970s yet only gained broad acceptance throughout the late 1970s according to the Ellen MacArthur Foundation (2014) through its three core principles to eliminate waste and extend product life while recovering natural systems. Business adoption of Circular Economy practices allows them to lower environmental damage and implement clean manufacturing approaches while developing sustainable sharing economy frameworks (Korhonen et al., 2018). The CE replicates natural ecosystem cycling through circular waste-to-input systems which maximize resource effectiveness (Kunzig, 2021: pg. 2). Despite unable to achieve exact natural efficiency levels human systems use CE to eliminate linear economy challenges through reduced resource consumption and technological advancements for environmental and economic durability (Chiappetta Jabbour et al., 2019: pg. 2).

2.3 Circular Economy and IoT

The scaling of Circular Economy (CE) depends heavily on technology for creating and analyzing data that supports complex circular supply chain requirements (Geissdoerfer et al., 2017: pg 3). The Internet of Things (IoT) emerges as a fundamental enabling technology which allows physical objects to communicate with each other using electronic components with sensor functions to exchange data. Manufacturing industries use the

Internet of Things to boost operational performance and stop defects and provide remote product support and better consumer interactions and boost customer loyalty according to Porter and Heppelmann (2014: pg 3). Organizations use this information system primarily to track assets and their status and geographic position. According to Ghisellini et al. (2016: pg 7) the Circular Economy demands clean fabrication approaches and renewable resource use along with established policies which deliver both environmental advantages and economic sustainability. Through IoT technology businesses optimize value chain operations by deploying automation to monitor resource usage across the entire lifespan from making to disposals while running big data assessments to achieve maximal efficiency. Through this combination of capabilities, the IoT supports the CE's environmental objectives (Ingemarsdotter et al., 2021 pg 8).

The IoT shows practical application in Circular Economy practices through investigations which show its use in lifecycle management (Kiritsis, 2011: pg 1), recycling optimization (Lindström et al., 2017 pg 1), and predictive maintenance from smart products (Moreno et al., 2017). Our understanding of IoT-directed derivatized business models comes from Ingemarsdotter et al. (2020 pg 8) and Pacelli et al. (2018 pg 3) who made proposals for IoT-enabled marketplaces in circular supply chains. The continued progress of IoT solutions in cycling economy practices faces several barriers due to data security issues and privacy concerns along with implementation difficulties (Alcayaga et al., 2019; Antikainen et al., 2018: pg 4). Through big data analysis patterns can be recognized alongside decision capabilities that enhance IoT capabilities but do not solve every challenge of CE transition (Sousa-Zomer et al., 2018: pg 4). The advancement of CE demands both deep comprehension about how IoT works with other technologies together with practical solutions that eliminate barriers to execution.

2.4 Smart Home Based on Internet of Things

IoT plays a crucial role in home automation by integrating smart devices for enhanced convenience, energy efficiency, and security. The advantages include mobile device control, lower installation costs, system stability, and ease of expansion. Home automation requires essential components such as security cameras, magnetic doors, and automated lighting. In 2016, S. Bharat et al. discussed various hardware and software applications, including RFID and wireless sensor networks (Bharath et al., 2017 pg 2).

The concept of domotics refers to the automation and intelligence of domestic environments (Kodali et al., 2016 pg 1). IoT-based automation systems enable control over lighting, heating, ventilation, air conditioning (HVAC), and appliances, improving the quality of life. While home automation has existed for years, no universal solution has been established. However, modern systems now serve as essential aids for the elderly and disabled, helping them manage home appliances efficiently (Li, & Yu, 2011 pg 4).

Remote access is another key feature of IoT-enabled homes. Using network traveler programs, home devices can be controlled via phone lines, wireless transmission, or the Internet. A reliable, cost-effective system can be built using Wi-Fi technology and NodeMCU ESP8266, which connects Arduino boards with electronic devices through a relay module (Sayeduzzaman et al., 2024 pg 6). A smartphone app facilitates serial communication with these boards, allowing remote operation of sensors and machinery. Most modern home automation systems cater to the elderly and disabled, enabling them to monitor children via security cameras or for other purposes. This system can be managed remotely from home, the office, or anywhere via a cloud-connected mobile application. Thus, smartphones can control household equipment from anywhere through cloud connectivity. Google Assistant enhances this experience by linking the voice-controlled automation cloud (Li, & Yu, 2011 pg 4).

IoT also enables energy-efficient smart homes through an effective Home Energy Management System (HEMS). According to Junyon Kim, a modern smart home integrates LED lighting, CCTV, infrared (IR) and ultrasonic (US) sensors, mobile devices, and networking systems to optimize power consumption (Kim, 2016 pg 4). Despite numerous research efforts, achieving power efficiency requires extensive testing and real-world implementation.

In the study “IoT-Based Smart Security and Home Automation System”, Kodali et al. (2016) developed a microcontroller-based smart home system that enhances ease of use and reliability. Energy management is essential for reducing consumption and maximizing efficiency. For instance, operating electronic devices during peak hours incurs higher costs than during off-peak hours. Motion sensors can automate lighting control, reducing unnecessary energy usage. Additionally, customers can be notified of peak-hour pricing, allowing them to take informed actions. The objective of such a system is to minimize energy waste through automated applications, which has led to an increased demand for professionals skilled in energy-efficient automation (Haque, et al., 2019 pg 2).

2.5 Theoretical Perspective

The dual lens framework from combining the Resource Based View (RBV) and the Diffusion of Innovation (DOI) Theory is to understand IoT based smart home technologies adoption and operationalization in the context of Circular Economy system.

According to RBV, firms can achieve long term market differentiation through differentiating deployment of unique assets including state faculty IoT infrastructure, data bring insights and sustainable operational processes that are challenging to replicate by competitors (Zhang et al., 2024 pp 16). For example, Google Nest, an IoT that enables energy usage, uses machine learning to learn a user's habits, optimizing the use of energy to promote circularity and limit waste (Nesmachnow et, al. 2025 pg 42). These technologies enable companies to design solutions that strike the tradeoff between the consumer's convenience and the reduction of environmental impact, which directly supports the Circular Economy priorities.

At the same time, DOI Theory looks at which social groups adopt new technologies and what are those adoption stages from the earliest adopters (initiators) to the most reluctant (waiters) (Mbatha, 2024). Adoption patterns for smart home innovations hinge on factors like practicality, intuitive design, and alignment with daily routines. Research shows that users put little emphasis on lifestyle enhancements, like energy savings or automatac controls, but continue to be hesitant if the learning curve is more intense then perceived benefits. Thus, effective training and clear communication of advantages are important in speeding up the acceptance (Valencia-Arias, et al. 2023 p3).

The combination of RBV and DOI not only provides insights into actionable pathways for advancing IoT smart homes in the Circular Economy, it also significantly strengthens the synergies found in the ten potential solutions. Consequently, RBV can direct firms so as to optimize their proprietary technologies constructing eco-efficient systems whilst DOI suggests that firms should tackle the barriers of adoption with special focus on providing targeted education and user centric design. Businesses can expand the consumer base and promote sustainable resource cycles by offering accessible, value based IoT solutions with focus on personal and environmental gains.

Together, these theories explain how technological and social adoption dynamics intersect, propelling the ability to scale innovations that marry economic viability with Circular

Economy goals, to drive systemic performance changes towards environmentally responsible resource utilization.

3 Research Methodology

Based on the Saunders' Research Onion Framework (Mphale, et al., 2024), this chapter outlines the research methodology of the study that systematically follows the study's approach. This chapter starts with definition of the research philosophy as show in figure 1 below, and then proceeds with the research approach and strategy that will be applicable symbiotically towards the outcome of the study. The data collection methods, i.e. primary and secondary, have been elaborated regarding sampling techniques. There is also a discussion in the chapter of data analysis techniques to lend to the reliability and validity of results. Research integrity is also maintained by addressing ethical considerations. Finally, the methodology framework provides a structured and systematic method of looking at the IoT based smart homes in the Circular Economy.

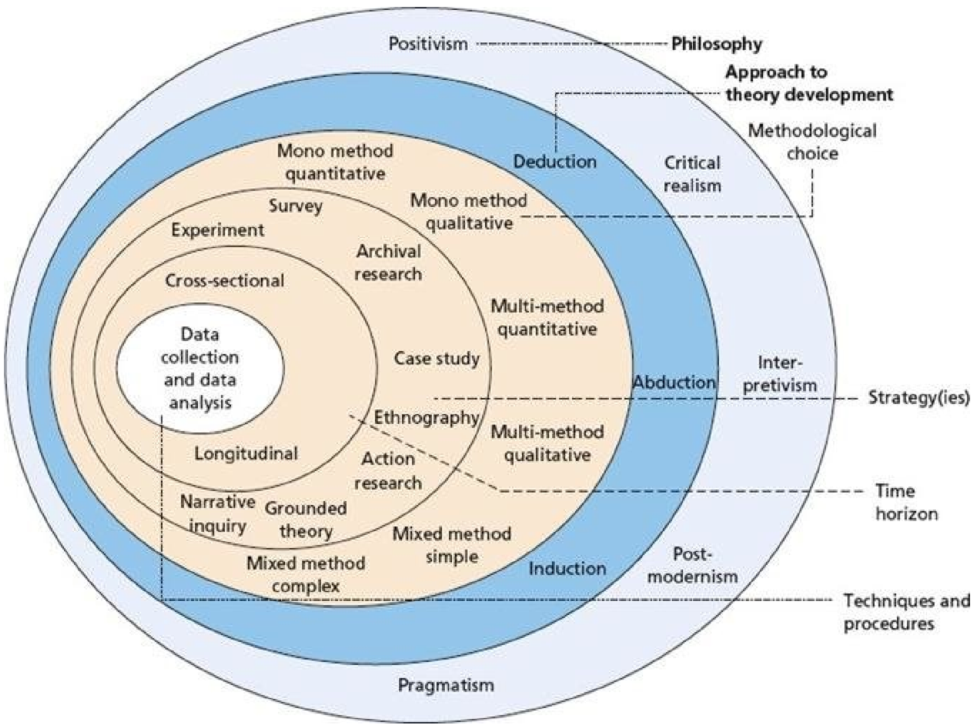

Figure 1: Saunders Research Onion Framework

3.1 Research Philosophy

Using a positivist research philosophy, this study adopted all the elements which include empirical evidence, data collection and analysis methodologies aimed at producing objective facts. The theory of positivism is relevant because it is grounded on observable and measurable facts as opposed to subject interpretation (Iovino, & Tsitsianis, 2020), therefore it is suitable for studying the quantifiable data produced by IoT based smart home system. Since smart homes produce data on energy efficiency, longevity of devices and resource management, positivism ensures a scientific and data driven handling. This philosophy regards the systematic data collection, statistical validation and visualization that is possible through the structured nature of survey questionnaires and interviews in accordance with this philosophy as working towards the reliable conclusions that arise from Circular Economy principles.

3.2 Research Approach

Deductive approach is chosen basically due to its hypothesis building and testing on already exiting theories of IoT, smart home automation and Circular Economy model. Deductive technique worked, with the theoretical frameworks leading to hypotheses that are checked in real world data (Melnikovas, 2018). The research investigates the ways in which IoT technology can minimize energy usage, uplift the life span of household devices and encourage resource recycling. An approach from deduction also guarantees that the research is carried out in a logical and structured hypothesis testing procedure to be able to systematically examine the role of IoT in smart homes for the adoption of the Circular Economy.

3.3 Research Strategy

A mixed method research strategy is used in the study, combining surveys and semi structured interviews to generate as much quantitative as possible and as much as qualitative insights as possible (Melnikovas, 2018). Structured and semi structured surveys include a set of questions that seek numerical data on the energy efficiency, automation usage and resource sustainability while semi structured interviews will investigate deep contextual experience and perceptions of the user regarding the use of IoT in smart homes. This combination allows for a comprehensive understanding of how IoT smart homes for

Circular Economy principles, including measurable impacts and individual experiences managing energy consumption and resource reuse.

3.4 Methodological Choice

To enhance the findings of the research, a mixed methods approach is selected between quantitative and qualitative data. The quantitative data collected through surveys provide insights into statistical trend in energy usage, device longevity and adoption for the Circular Economy towards smart home systems, while the qualitative data obtained from interviews will talk about challenges, motivation and users' perspective in which smart home system IoT can be integrated. With such a dual approach, data triangulation is performed, which increases research validity and provides a more comprehensive evaluation of the smart home. Finally, a study that combines numerical analysis with experiential insights assures a rigorous as well as comprehensive evaluation of how IoT is going to influence the Circular Economy.

3.5 Time Horizon

The study adopts a cross-sectional time horizon since data gathered in one instance of time to assess the current state of IoT adoption, problems faced and the extent to which it enriches the practice of Circular Economy. The present approach allows for the simulation of the present trends in use and behavior regarding smart home sustainability with no requirement for long term tracking. The cross-sectional design is used since the purpose of the study is to figure out how IoT based smart homes are employed currently in order to be utilizing resource efficiency, device longevity, and automation in a Circular Economy model.

3.6 Techniques and Procedure

Survey questionnaires and semi structured interviews conducted to collect the data from 30 smart home users. In survey, closed ended questions were asked to reveal quantifiable data about energy efficiency, automation adoption, and resource recycling behaviors. The qualitative insight into the challenges and optimization strategy for IoT adoption in smart home adoption was explored through semi-structured interviews. Statistical techniques such as descriptive statistics, correlation analysis and regression analysis were used to process survey responses to identify the trends and correlations in the IoT adoption and energy efficiency. Interview data will be thematic coded to extract key insights and patterns of experiences from participants. This methodological framework has the advantage of providing structured evaluation of how IoT based smart homes meet with the principle of Circular Economy while maintaining practicality and efficiency.

3.7 Ethical Considerations

This research abides by strict ethical principles to protect the integrity and confidentiality on how research process is carried out. In terms of surveys and interviews to be conducted were fully informed to participants about the study's objectives and each participant would give his or her informed consent. It was ensured that the collected data is safe and not associated with individual participants to maintain anonymity and confidentiality. The participants had the right to withdraw anytime, without consequence. Responses will also be implemented with data security ensuring that they remain private from unauthorized access. The study uses ethical standards in research, carrying fair play, transparency and respect of participants' rights.

4 Data Analysis, Findings and Results

The analysis of the collected data by survey questionnaires and interviews in this chapter is presented. It begins by delving into survey responses, unpacking key trends regarding the adoption of IoT, energy efficiency, device longevity, and Circular Economy practices with graphs and charts. The qualitative findings on the interviews are coded into theme to discover the common causes and optimization possibilities. This discussion is then related to the research questions posed and the literature reviewed to offer insights on the Circular Economy goals that can be achieved through the use of the IoT based smart home systems.

4.1 Findings and Discussion

4.1.1 Demographic Analysis of Respondents

IoT based smart home as an application can also be investigated in this context in the Circular Economy. This goal was achieved through a two-part questionnaire. The first section focuses on gathering demographic data from respondents, including age, gender, and smart home usage duration. The second section consists of Likert-scale questions designed to evaluate the role of IoT in energy efficiency, device longevity, and Circular Economy adoption

According to the demographic findings, a significant portion of respondents falls within the 26 to 35 age group (37%), followed by 32% aged 18 to 25. The 36 to 45 age group accounts for 21%, while 10% are above 45 years old, graphical representation is below. The distribution of age groups suggests that IoT-based smart homes are predominantly used by younger to middle-aged individuals, who are likely more tech-savvy and open to adopting smart home automation for enhanced energy efficiency.

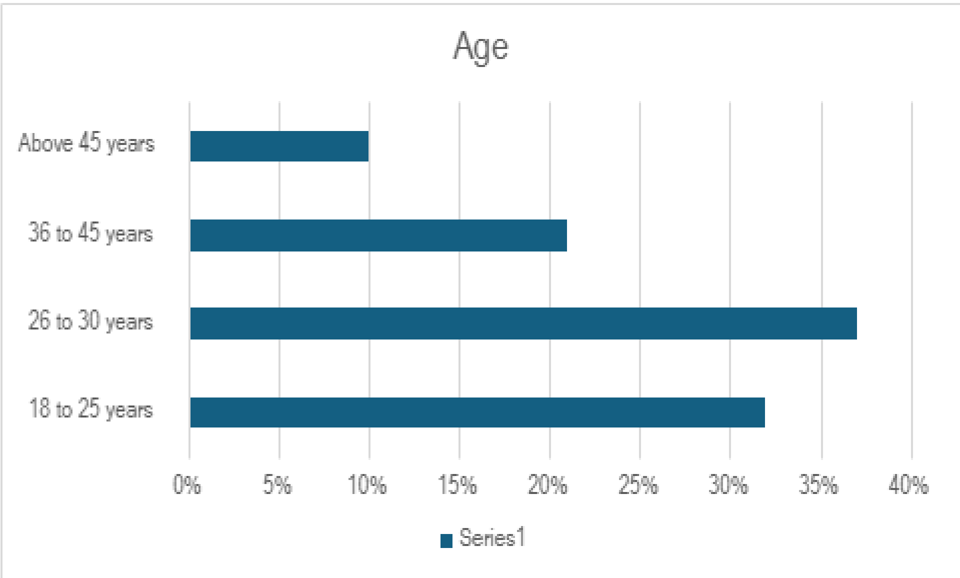

Figure 2: Age Distribution of Respondents

Similarly, the gender distribution indicates that 55% of respondents are male, 45% are female, and 5% preferred not to disclose their gender as shown in figure 3. These findings suggest that IoT-based smart home technology adoption is slightly higher among males, possibly due to greater familiarity with smart devices and home automation systems.

However, the growing adoption among females indicates a broadening market that caters to various user demographics.

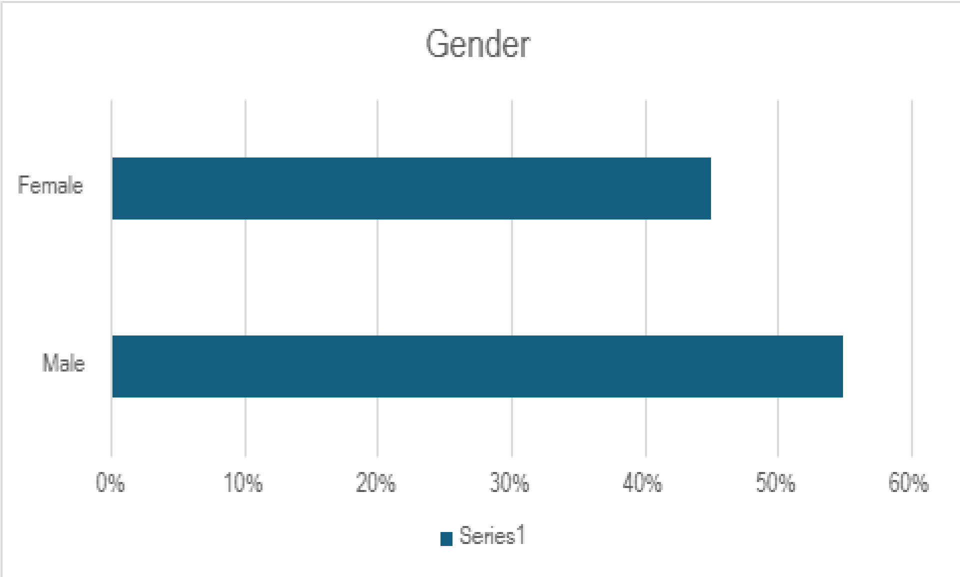

Figure 3: Gender Distribution of Respondents

Regarding smart home usage duration, the findings and graph in figure 4 below reveal that 42% of respondents have been using smart home technology for 3 to 5 years, followed by 28% who have used it for 1 to 2 years. Additionally, 20% have been using smart home automation for more than 5 years, while 10% are relatively new users with less than 1 year of experience. This implies that most respondents have extensive experience regarding IoT based smart home that makes them potentially have experience that can render meaningful feedback on energy efficiency, device sustainability as well as resource recycling.

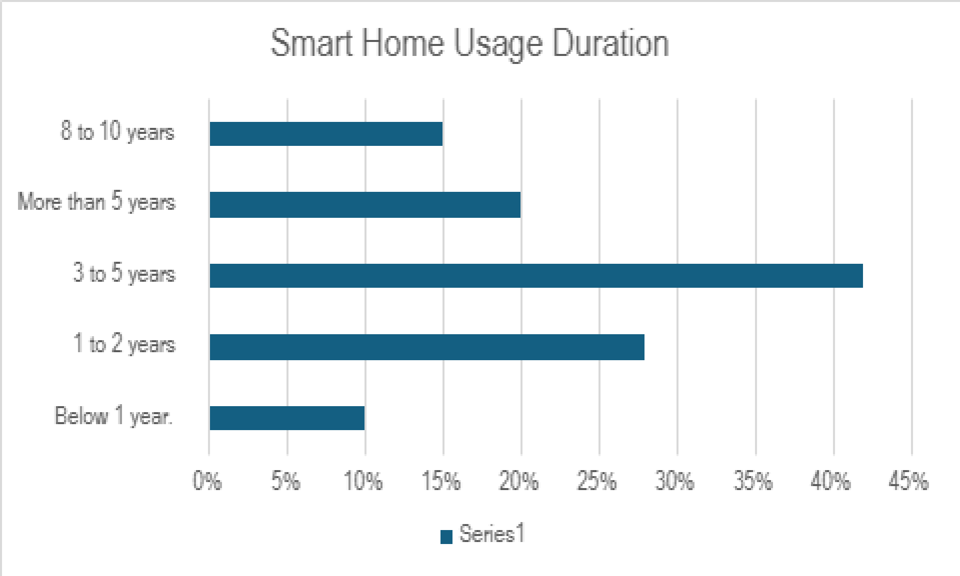

Figure 4: Smart Home Usage Duration

4.1.2 Descriptive Statistics:

Statistics

Variable	N	N*	Mean	SE Mean	StDev	Minimum	Q1	Median
energy efficiency	30	0	3.36667	0.237241	1.29943	1	2	3.5
energy efficiency-1	30	0	3.03333	0.246741	1.35146	1	2	3
increased lifespan	30	0	3.03333	0.285606	1.56433	1	1.75	3.5
increased lifespan-1	30	0	2.66667	0.246041	1.34762	1	1	3
promoting circular economy	30	0	3.63333	0.222232	1.21721	1	3	4
obstacle 1: increseased cost	30	0	2.4	0.265226	1.45270	1	1	2
Obstacle 2: privacy & security	30	0	2.86667	0.252497	1.38298	1	1.75	3
improvements required	30	0	2.66667	0.241325	1.32179	1	1	3
improvements required-1	30	0	2.73333	0.253406	1.38796	1	1	3
improvements required-2	30	0	3.13333	0.261443	1.43198	1	1.75	3

Variable	Q3	Maximum
energy efficiency	4.25	5
energy efficiency-1	4	5
increased lifespan	4.25	5
increased lifespan-1	3.25	5
promoting circular economy	5	5
obstacle 1: increseased cost	4	5
Obstacle 2: privacy & security	4	5
improvements required	4	5
improvements required-1	4	5
improvements required-2	4	5

Figure 5: Descriptive Statistics

- Energy Efficiency and Smart Home Automation

The energy efficiency mean score of energy efficiency (3.37) implies that the respondents approve the fact that IoT based automation hugely benefits energy optimization in smart homes. The mean score at 3.5 means that the responses are slightly skewed toward agreement, and the standard deviation (1.30) means that the opinions are moderately dispersed. This is consistent with Das et al. (2023) who showed that smart home automation can reduce energy consumption by up to 30 percent through the use of automated device usage and the learning of user preferences.

- IoT and Device Longevity

The score of 3.03 in increased lifespan signifies a moderate agreement that IoT enabled automation reduces overuse and inefficiency of household appliances and thus helps it extend life. The higher value of standard deviation (1.56) suggests higher variability in responses, which means that not all the users have experienced a large increase in the observed objective. Shirvani and Ghasemshirazi (2024) support it by proving that IoT enabled smart home systems like predictive maintenance technologies contribute to longer appliances by preventing such appliances from being excessive to wear and tear.

- IoT's Role in Promoting Circular Economy

With a mean score of 3.63, respondents tend to agree that IoT in smart homes plays a crucial role in supporting Circular Economy principles, such as resource reuse, energy conservation, and recycling automation. The standard deviation (1.21) suggests relatively consistent agreement among respondents. This is reinforced by Wirani et al. (2024), who identified IoT as a key enabler of Circular Economy models by enhancing waste tracking, optimizing resource consumption, and improving sustainable product life cycles.

- Obstacles: Cost and Security Concerns

The high initial cost of IoT devices had a mean score of 2.4, indicating a generally neutral to slightly negative perception, with a standard deviation of 1.45, showing variability in concerns. Similarly, data privacy and security concerns (mean = 2.67, SD = 1.38) suggest that a significant portion of respondents sees these as obstacles to IoT adoption. Mora et al. (2017) highlighted that security risks associated with IoT networks, including data breaches and hacking vulnerabilities, remain a primary concern among potential adopters.

- Improvements Needed in IoT-Based Smart Homes

The mean scores for required improvements (2.67–2.73) suggest that respondents neither strongly agree nor disagree about the sufficiency of current smart home frameworks in fully aligning with Circular Economy principles. However, the relatively high standard deviation (~1.3) suggests varied opinions on what improvements are necessary. This is in line with Ingemarsdotter, et al., (2019), who emphasized that interoperability issues, lack of standardization, and energy optimization gaps hinder the full potential of IoT in achieving a sustainable Circular Economy.

4.1.3 Correlation Analysis

Correlations

	energy efficiency	energy efficiency-1	increased lifespan	increased lifespan-1	promoting circular economy	obstacle 1: increseased cost	Obstacle 2: privacy & security	improvements required	improvements required-1
energy efficiency-1	0.071								
increased lifespan	0.028	0.228							
increased lifespan-1	-0.026	0.025	-0.191						
promoting circular economy	-0.021	-0.097	0.007	0.112					
obstacle 1: increseased cost	0.121	0.379	-0.036	0.035	0.008				
Obstacle 2: privacy & security	-0.125	-0.219	-0.062	-0.136	0.154	0.130			
improvements required	-0.027	0.354	0.156	0.090	-0.057	0.144	-0.082		
improvements required-1	0.190	0.005	0.131	0.025	0.001	0.072	0.178	-0.031	
improvements required-2	-0.342	-0.234	-0.310	0.131	-0.050	0.206	0.183	-0.194	0.192

Figure 6: Correlation Analysis

Relationship Between Energy Efficiency and Other Factors

- Energy efficiency and increased lifespan (r = 0.228) show a weak positive correlation, suggesting that as smart home energy efficiency increases, appliances may last longer due to better power management. However, the low correlation suggests that other factors besides energy efficiency contribute to extending device lifespan.
- Energy efficiency and Circular Economy (r = -0.021) show a negligible negative correlation, indicating no meaningful relationship. This suggests that while IoT-based energy efficiency is beneficial, it does not directly drive Circular Economy adoption.

Relationship Between Circular Economy and Smart Home Adoption:

- Promoting Circular Economy and increased lifespan (r = 0.112) suggests a very weak positive correlation, implying that smart home IoT adoption may slightly influence device longevity but is not a primary driver.
- Promoting Circular Economy and improvements required (r = -0.057) shows a weak negative correlation, indicating that the need for improvements does not significantly affect Circular Economy perceptions.

Impact of Cost and Security Concerns on IoT Adoption:

- Obstacle 1: Increased cost negatively correlates with energy efficiency (r = -0.125) and device lifespan (r = -0.062), indicating that higher costs discourage energy-efficient practices and limit device longevity benefits.
- Obstacle 2: Privacy & security concerns negatively correlate with energy efficiency (r = -0.219) and increased lifespan (r = -0.136), meaning that users with security concerns are less likely to optimize energy use or benefit from longer-lasting appliances. This aligns with prior research that highlights privacy concerns as a major barrier to smart home adoption (Mora et al., 2020).

Relationship Between Need for Improvements and Smart Home Functionality:

- Improvements required and energy efficiency (r = 0.354) suggest a moderate positive correlation, meaning that users who recognize the need for system improvements also see potential for better energy efficiency.
- Improvements required and increased lifespan (r = 0.131) indicate a weak positive correlation, suggesting that better smart home optimization could enhance device longevity but is not the sole determinant.

The correlation results suggest that while energy efficiency and smart home adoption moderately contribute to Circular Economy principles, factors such as cost, security, and system limitations significantly hinder their full impact. Addressing cost-related barriers, improving security measures, and refining smart home frameworks could strengthen the role of IoT in sustainability and resource optimization.

4.1.4 Regression Analysis

The regression analysis was conducted to examine the impact of energy efficiency, device lifespan, cost and security concerns, and smart home improvements on the adoption of IoT-based smart home systems within a Circular Economy framework.

Coefficients

Term	Coef	SE Coef	T-Value	P-Value	VIF
Constant	1.86	4.10	0.45	0.670	
energy efficiency	0.184	0.533	0.34	0.744	5.67
energy efficiency-1	0.143	0.476	0.30	0.776	4.90
increased lifespan	0.203	0.289	0.70	0.513	2.43
increased lifespan-1	0.165	0.644	0.26	0.808	8.92
obstacle 1: increseased cost					
2	0.17	1.90	0.09	0.930	3.97
3	-0.37	1.52	-0.24	0.818	4.50
4	-1.04	1.79	-0.58	0.587	5.48
5	-0.62	1.81	-0.34	0.747	3.62
Obstacle 2: privacy & security					
2	-1.66	2.64	-0.63	0.558	11.86
3	0.09	1.35	0.07	0.947	3.99
4	-0.18	1.37	-0.13	0.902	4.14
5	0.36	1.88	0.19	0.857	5.02
improvements required					
2	-0.24	2.82	-0.08	0.937	15.61
3	-0.94	1.78	-0.53	0.620	6.19
4	0.51	2.13	0.24	0.819	10.82
5	-0.83	1.83	-0.46	0.668	2.56
improvements required-1					
2	-0.58	2.04	-0.28	0.789	4.59
3	0.51	2.38	0.21	0.839	13.57
4	1.19	1.81	0.66	0.539	7.15
5	-1.81	2.04	-0.89	0.414	4.57
improvements required-2					
2	1.23	2.82	0.44	0.680	3.14
3	-0.24	1.99	-0.12	0.909	10.22
4	1.30	2.41	0.54	0.612	12.72
5	-0.43	1.82	-0.24	0.821	6.47

Model Summary

S	R-sq	R-sq(adj)	R-sq(pred)
1.56485	71.50%	0.00%	*

Figure 7: Regression Analysis

1. Coefficients and Predictive Power of Variables

The coefficient values indicate the direction and strength of relationships between predictor variables and the dependent variable. The energy efficiency coefficient ($\beta = 0.184$, $p = 0.744$) suggests a positive but statistically insignificant impact on IoT-based smart home adoption. Similarly, the device lifespan coefficient ($\beta = 0.203$, $p = 0.513$) indicates that while increased lifespan may influence smart home adoption, its effect is not statistically significant. These findings align with previous studies, such as Rejeb et al. (2022), which found that while IoT-driven efficiency and longevity enhance sustainability, adoption is often influenced by external factors like cost and security concerns.

2. Impact of Cost and Security Concerns:

The regression results show that cost ($\beta = -0.62$, $p = 0.747$) and security concerns ($\beta = 0.36$, $p = 0.857$) do not significantly predict IoT adoption. This suggests that while cost and privacy concerns are commonly perceived as barriers, they may not be the strongest determinants for adoption. Similar results were found in Gheorghe (2023), which highlighted that smart home users often weigh functionality over privacy concerns, provided they receive tangible benefits in energy savings and automation.

3. Role of Smart Home System Improvements:

The coefficients for required improvements ($\beta = -0.24$ to 1.23, p-values > 0.6) suggest that respondents recognize the need for better frameworks but do not see them as immediate barriers to adoption. This is supported by Mora et al. (2020), which emphasized that while users desire continuous improvements in IoT systems, the decision to adopt is more strongly influenced by usability and immediate economic benefits.

4. ANOVA and Model Significance

The ANOVA table shows an F-statistic of 0.52 ($p = 0.871$), indicating that the overall regression model is not statistically significant. This suggests that the combined effect of energy efficiency, cost, security, and system improvements does not significantly predict IoT adoption within the surveyed sample. However, a larger sample or inclusion of additional factors such as government incentives and behavioral influences might yield different results, as indicated by Alam et al. (2021), who found that financial incentives play a crucial role in IoT adoption for sustainable living.

The regression results indicate that while energy efficiency, device longevity, and Circular Economy alignment are perceived benefits of IoT-based smart homes, they predict adoption within this dataset. Cost and security concerns, although often discussed as major obstacles, show predictive power. This suggests that IoT adoption in smart homes may be driven by a combination of factors beyond just economic and technological aspects, such as lifestyle preferences and government policies. Future research could explore additional behavioral and policy-related variables to gain a more comprehensive understanding of IoT adoption patterns in Circular Economy frameworks.

4.2 Thematic Analysis

The thematic analysis of interview responses provides insights into how IoT-based smart home systems impact energy efficiency, sustainability, and Circular Economy adoption, while also highlighting challenges and potential improvements.

Interview Question	Theme	Codes
In what ways has IoT technology in your smart home influenced your energy consumption and efficiency?	**Energy Optimization**	Automated energy adjustments, Smart scheduling for efficiency, Energy consumption tracking
	User Behavior and Control	Customizable energy usage settings, User adaptation to automation, Behavioral impact on energy use
	Cost Savings	Lower electricity bills, Reduction in unnecessary energy usage, Long-term financial benefits
What challenges have you faced in integrating smart home technologies with sustainable practices such as resource recycling and device longevity?	**Cost Barriers**	High initial investment, Limited access to affordable devices, Expensive smart appliances

	Security Concerns	Data privacy risks, Risk of hacking and breaches, Lack of control over personal data
	Technical Complexity	Difficulties in system setup, Compatibility issues with existing devices, Need for professional installation
How do you think smart home systems can be further optimized to align with Circular Economy principles while maintaining practical functionality?	**Improved Interoperability**	Standardized IoT communication, Integration challenges across platforms, Lack of universal compatibility
	Enhanced Predictive Maintenance	AI-driven device longevity monitoring, Remote diagnostics for appliances, Automated alerts for device health
	Smart Recycling Integration	Automated waste sorting and disposal, IoT-driven recycling reminders, Tracking recyclable material usage

Regarding energy consumption and efficiency, participants largely agreed that IoT automation reduces energy waste and optimizes electricity usage. One respondent mentioned, “My smart thermostat automatically adjusts heating and cooling based on my schedule, which has significantly lowered my energy bills.” Another participant highlighted the importance of customizable settings, stating, “I prefer manual control over smart lighting, but the scheduling feature helps me avoid unnecessary electricity use.”

When asked about challenges in integrating smart homes with sustainability, cost barriers and technical complexity were major concerns. One respondent noted, “I wanted to install a full smart home system, but the high upfront costs discouraged me.” Another emphasized security risks, saying, “I worry about my personal data being shared through smart devices; it makes me hesitant to use some IoT features.” These responses align with findings that cost and privacy issues remain key adoption barriers.

In discussing ways to optimize smart homes for Circular Economy principles, many respondents suggested improving interoperability and predictive maintenance. One user shared, “If different smart home brands worked together seamlessly, I would invest more in IoT automation.” Another participant suggested automated waste sorting, stating, “A smart bin that categorizes recyclables would make my home’s sustainability efforts easier.”

While participants recognize the energy and sustainability benefits of IoT, they emphasize the need for affordable solutions, stronger security measures, and improved system integration to fully leverage IoT in a Circular Economy framework.

5 Conclusion and Recommendation

In this chapter, the findings of the study are summarized and the outcomes of smart homes based on IoT are discussed with an emphasis on the impact on energy efficiency, device longevity along with the adoption in Circular Economy. Moreover, it responds to these identified challenges, such as the cost and security concerns and proposes solution for boosting sustainability and user adoption of the smart home frameworks.

5.1 Conclusion

This thesis identified key research objectives and questions in the context of applying and prospecting IoT based smart home systems in a Circular Economy approach. The findings are corroborated by the fact that the utilization of IOTA technologies allows for the optimization of energy use in smart homes via automation, real-time monitoring, and adaptive energy management. Those energy efficiency gains, however, also depend on factors of user engagement, system interoperability and smart grid integration.

The study looks at how smart home systems could use IoT to extend device lifespan and how at the same time promote resource recycling by reducing unnecessary wear and tear on household appliances through IoT enabled predictive maintenance and automation. While users appreciate these benefits, adoption remains slow because awareness is low and costs high at the outset. Smart home automation has a contribution in development of waste management and recycling, but it is still reserved in Circular Economy models in more structured ways.

In addition, the research also pointed out that cost and data security issues were key hindrances to integrating IoT based smart homes with the Circular Economy principles. Some of these factors do dictate adoption among users, but not the biggest reason. Technological limitations, lack of standardized frameworks and system inefficiencies are the bigger challenges. To address these barriers, we need to work on system improvement while improving security protocols and choose a more cost-effective deployment model.

The study went to see how a smart home framework can be created in the principals of Circular Economy and make sure it is operationally practical. The results indicate that home automation enabled by IoT can contribute to sustainability goals, but for this to happen policies must support their implementation, interoperability must be seamless and users must become more aware of the benefits. Overall, smart homes enabled by IoT have a lot of promise for the adoption of the Circular Economy, but to achieve their full potential will need to overcome technological, economic, and behavioral barriers.

5.2 Recommendations

Several strategic measures would need to be taken to increase the adoption and effectiveness of IoT based smart home systems within a Circular Economy framework. Interoperability and standardization of the system must be high in priority to make sure that the smart home devices and platforms are congruent. The adoption among the users will be improved by reducing the inefficiency using standardized communication protocols. Moreover, cost remains very high and financial incentives, tax reductions or subsidies from governments and industry stakeholders can lower the costs of powering IoT enabled smart homes. To encourage wider adoption, the manufacturers should concentrate on developing cost effective and scalable solutions. To add trust among users, data privacy and security should be addressed through encryption, user control over data, and compliance with data protection rules.

Transparency in how data is collected and used may provide more assurance regarding one's privacy. Additionally, awareness campaigns and educational programs are necessary because many of the users only know how IoT can improve energy efficiency and sustainability, and do not see how. To increase engagement and reap the smart home automation benefits, user friendly manuals coupled with interactive training sessions will be given. Moreover, considering the development of Circular Economy oriented smart home frameworks is a necessity. The sustainable goals would be supported if the future smart home designs integrated the predictive maintenance, automatic recycling and the energy efficient features. Device longevity and minimized electronic waste will be relieved as manufacturers will also need to explore modular, upgradeable designs. These recommendations will help implement more efficient, sustainable, and adopted IoT based smart home systems to support their transition to Circular Economy principles leading to long term user satisfaction and adoption.

5.3 Limitations of the Study

This study has limitations which should be acknowledged despite its valuable insight. Since the sample size is limited to 30 respondents, it represents the portion of the whole population of the IoT based smart home users. This might help find a more generalizable finding. Second, the data for this study were from self-reported survey data, which could be biased, personal perceptions, and variable in response. It may be that participants responded as they did because of their lack of understanding about what energy efficiency is or device longevity or Circular Economy concepts. The third point is that the study’s main focus was on quantitative analysis, and as a result, the depth of knowledge gained in terms of user experiences, challenges, and behavioral factors propelling IoT adoption is greatly limited. The study also failed to take into account effects of countries' government policies, economic conditions, and regional differences in smart home adoption. Research in the future should involve a larger and more diverse sample along with the use of mixed methods to bring a better understanding of the adoption of IoT in Circular Economy framework.

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Appendix

Appendix 1: Survey Questionnaire

Below are a few questions regarding IoT-based smart homes and their role in energy efficiency and sustainability. Your responses will help in understanding smart home adoption and its impact on the Circular Economy. I assure you that all your information will be kept confidential.

- **Demographic Information**

1. Age

- 18-25
- 26-35
- 36-45
- Above 45

2. Gender

- Male
- Female

3. Smart Home Usage Duration

- Less than 1 year
- 1-2 years
- 3-5 years
- More than 5 years

- **Survey Questionnaire**

Please indicate your level of agreement with the following statements on a scale from 1 (Strongly Disagree) to 5 (Strongly Agree).

1. IoT-based smart home systems significantly enhance energy efficiency by automating device usage.
2. My smart home system helps in reducing electricity consumption through optimized energy management.
3. IoT devices in my home contribute to extending the lifespan of household appliances by preventing overuse or inefficiency.
4. I actively engage in resource reuse and recycling practices due to my smart home automation system.
5. The integration of IoT technology in smart homes plays a vital role in promoting Circular Economy principles.
6. The high initial cost of IoT-enabled smart home systems is a major obstacle to their widespread adoption.
7. Data privacy and security concerns prevent me from fully utilizing IoT-enabled smart home features.
8. I believe that improvements in smart home frameworks can enhance their alignment with Circular Economy goals.
9. The current smart home system I use provides practical functionality while also being environmentally sustainable.
10. I would be more likely to adopt a smart home system if it provided clear benefits in energy savings, device longevity, and waste reduction.

- **Interview Questions (Open-Ended)**

Q1: In what ways has IoT technology in your smart home influenced your energy consumption and efficiency?

Q2: What challenges have you faced in integrating smart home technologies with sustainable practices such as resource recycling and device longevity?

Q3: How do you think smart home systems can be further optimized to align with Circular Economy principles while maintaining practical functionality?

Appendix 2: Survey Results:

A	B	C	D	E
Q1: IoT-based smart home	Q2: My smart home system helps	Q3: IoT devices in my home	Q4: I actively engage in resour	Q5: The integration of IoT te
4	3	2	3	2
5	4	4	1	4
3	4	5	3	5
5	1	2	3	3
5	3	2	1	1
2	5	4	3	4
3	3	2	5	5
3	5	2	2	4
3	1	4	2	5
5	2	4	1	5
4	4	1	4	3
3	1	5	1	5
5	4	5	4	4
2	2	2	2	5
4	2	5	1	3
2	1	2	5	3
4	2	1	3	4
5	5	4	4	2
1	2	4	3	2
4	4	4	3	5
2	4	5	1	1
5	4	1	3	5
4	4	5	5	4
1	5	5	3	4
1	3	1	1	4
3	1	1	5	4
3	4	1	2	4
2	2	1	3	3
4	4	4	1	2
4	2	3	2	4

F	G	H	I	J
Q6: The high initial cost of Io	Q7: Data privacy and secu	Q8: I believe that improveme	Q9: The current smart home syst	Q10: I would be more like
1	1	3	3	3
1	3	4	1	1
1	1	3	1	1
1	2	2	3	4
3	2	3	3	3
1	4	3	3	3
4	5	4	4	5
5	1	4	1	3
1	1	1	4	3
3	3	1	3	3
3	2	2	1	2
1	5	1	4	5
5	4	3	4	1
1	2	4	3	4
3	4	1	1	1
2	3	1	3	5
4	3	2	1	4
3	1	2	5	5
1	5	3	2	3
4	4	4	2	4
1	2	2	2	3
1	3	1	3	1
2	1	4	5	1
4	1	4	1	4
4	4	1	4	4
2	3	2	1	5
3	5	1	4	5
1	3	4	1	3
5	4	5	5	4
1	4	5	4	1