

LAPORAN KERJA PRAKTEK

**“GREEN AND SMART BUILDING TECHNOLOGY AS AN
INNOVATION IN SUSTAINABLE CONSTRUCTION”**

INTERNATIONAL COURSE PROGRAM (ICP)



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LEMBAR PENGESAHAN
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GREEN AND SMART BUILDING TECHNOLOGY AS AN
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PREFACE

All praise and gratitude to Allah Almighty for His blessings and guidance, which have enabled the author to complete this project report for the International Course Program (ICP) entitled: **“GREEN AND SMART BUILDING TECHNOLOGY AS AN INOVATION IN SUTAINANBLE CONSTRUCTION**his report was prepared as part of the final assignment for the International Course Program (ICP) at Universitas Medan Area. The project integrates renewable energy concepts by harnessing sunlight—utilizing reflective mirrors for natural illumination—and implementing a solar-powered automated lighting system to provide effective lighting solutions.

The author would like to express sincere gratitude to all parties who have contributed to the completion of this report:

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The author realizes that this report is not without limitations and shortcomings. Therefore, constructive feedback and suggestions for improvement are highly appreciated. Finally, it is hoped that this report can provide both academic benefits and inspiration for future developments in renewable energy technology.

Medan, 25st September 2026



Bintang R.Marpaung

ABSTRACT

This study aims to examine the implementation of green and smart building technologies as innovations in sustainable construction in Medan, identify the challenges encountered, and formulate strategies to enhance adoption. Employing a qualitative approach with in-depth interviews, field observations, and documentation studies, this research collected data from various stakeholders in the construction sector. The findings indicate that green building technologies are implemented through the use of eco-friendly materials, architectural designs maximizing natural lighting and ventilation, and integrated waste management systems, driven by environmental awareness and potential long-term operational cost savings. Meanwhile, smart building technologies are applied through building automation systems such as automated energy management, sensor-based lighting control, and integrated IoT security systems, aimed at improving operational efficiency and occupant comfort, primarily in modern commercial buildings. Key challenges include high initial investment costs, a shortage of competent experts, limited local government regulations and incentives, and a lack of market education.

To boost adoption, proposed strategies include developing clear regulations and fiscal incentives, enhancing human resource capacity through training, market education campaigns, and strong cross-sector collaboration. This study extends the understanding of sustainable innovation adoption dynamics in the Indonesian urban context, highlighting the importance of a supportive ecosystem for more widespread green and smart construction development. The findings confirm that construction sustainability relies not only on technology but also on policy, awareness, and human resource capabilities.

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CHAPTER I INTRODUCTION

1.1 Background

Global climate change and natural resource scarcity are major concerns across various sectors, including the construction industry. The building and construction sector consumes significant energy, accounting for 30% of total global energy consumption, and contributes one-third of greenhouse gas emissions, equivalent to 450 million tons of CO₂. Without significant intervention, carbon emissions from this sector are projected to reach 1.5 billion tons of CO₂ by 2030. The emphasis on sustainable development in the construction sector is a response to the urgent need to improve the environmental, economic, and social sustainability of buildings (Gallo et al., 2021).

Sustainability in construction is no longer an option but a necessity to mitigate negative environmental impacts. Conventional buildings are often associated with environmental degradation, high energy demand, pollutant emissions, and unsafe working conditions (Silva et al., 2023). Green buildings have emerged as a fundamental solution to address these challenges, offering significant potential for moving towards sustainable development, particularly in the context of climate change (Meena et al., 2022). The adoption of more environmentally friendly construction practices is crucial to ensure a balanced use of energy, water, and other resources.

Indonesia, as a developing country, is committed to reducing greenhouse gas (GHG) emissions. The target for GHG emission reduction is 31.89% through its own efforts and 43.20% with international support by 2030 (September 2023). Total GHG emissions in Indonesia in 2022 reached 1,008,178 Gg CO₂e, with business sectors, including industry and construction, contributing 696,505 Gg CO₂e or 78.50% of total national emissions. This figure demonstrates the urgency for the Indonesian construction sector to adopt innovative technologies that support sustainability and energy efficiency.

Indonesian government regulations increasingly demonstrate support for sustainable development. Several regulations have been issued, including Minister of Public Works and Housing Regulation No. 2 of 2015 concerning Green

Buildings, Minister of Public Works and Housing Regulation No. 21 of 2021 concerning Green Building Performance Assessment, and Minister of Public Works and Housing Regulation No. 10 of 2023 concerning Smart Buildings (BGC). These policies represent a concrete government effort to promote energy efficiency in the building sector, which is projected to save up to IDR 2.8 trillion in energy costs per year and reduce millions of tons of CO₂ emissions. The importance of adopting environmentally friendly practices to mitigate the environmental impact of the concrete construction industry is emphasized, with a review of trends and opportunities in sustainable concrete construction (Nilimaa, 2023).

The adoption of green and smart technology in Indonesia is showing a positive trend, although still limited. As of April 2026, 504 buildings across Indonesia had been certified green, either through the Greenship scheme or other standards. As of July 2025, the International Finance Corporation (IFC) reported 200 EDGE-certified building projects in Indonesia, totaling 4.3 million square meters, including 27,620 homes. Projections indicate that smart and green building development in Indonesia has the potential to reach 25% of the market by 2025, signaling a growing interest in sustainable innovation (November 2024).

Mass adoption among property developers remains a challenge. Of the 4,000 active property developers in Indonesia, only around 5%, or 200 companies, have committed to implementing green building certification. This limitation indicates that the implementation of sustainable practices requires further encouragement, both in terms of incentives and increased awareness. Green development reduces carbon emissions by up to 100,000 tons per year, saves 120,000 megawatt hours (MWh) of energy, and reduces water consumption by up to 4.7 million cubic meters annually.

Medan, as one of Indonesia's major cities, holds significant potential for the application of green and smart building technologies. Infrastructure growth and the construction of new buildings in Medan continue to occur, in line with the increase in Gross Domestic Product (GDP) from the construction sector in Indonesia, which reached 10.06% in the third quarter of 2024. This increase indicates high construction activity, making the environmental impact of development in Medan a significant concern. The average energy consumption intensity of office buildings

in Indonesia is 160 kWh/m²/year, indicating significant potential for energy savings through smart technologies (March 2026).

The adoption of smart building technology (SBT) in developing countries, including Indonesia, still faces challenges despite its significant benefits (Ejidike & Mewomo, 2023). SBT applications offer energy efficiency, lower building maintenance and operation costs, and potential job creation. The implementation of smart buildings in Indonesia has resulted in energy savings from 765,228.16 kWh to 499,067.01 kWh, equivalent to a 34.78% reduction. The lack of attention from construction professionals to SBT adoption in developing countries indicates a gap in understanding and implementation.

In the context of universities in the Medan area, discussions on green and smart building technologies as innovations in sustainable construction are highly relevant. Academic institutions play a crucial role in developing and disseminating innovative construction practices. The integration of advanced technologies with a human-centered approach, sustainable practices, and resilience considerations are hallmarks of the Construction 5.0 concept (Yitmen et al., 2024). Universities can be pioneers in the research and development of these technologies and educate future generations of civil engineers to be competent in their application.

Several previous studies have examined innovations in sustainable construction. Li et al. (2024) explored the opportunities and challenges in facilitating Construction 5.0 for smart, sustainable, and resilient buildings, finding that the adoption of human-centric technologies, maintaining resilience, and sustaining sustainability are crucial. Gallo et al. (2021) analyzed the sustainability performance of industrialized precast building technologies, finding that prefabrication can improve building sustainability in terms of predictability, product and process quality, and improved worker safety. Iwuanyanwu et al. (2024) reviewed trends and opportunities in sustainable concrete construction, highlighting the importance of environmentally friendly practices for mitigating the industry's environmental impacts, and discussing the technical, economic, and social challenges in implementation.

Ejidike and Mewomo (2023) identified the benefits of adopting smart building technologies (SBTs) in developing countries, including energy efficiency

and reduced operational costs, although adoption remains low. Bungău et al. (2022) evaluated green buildings in the context of sustainable development, clarifying concepts and application principles while integrating green materials and the circular economy, but acknowledged low public acceptance due to suboptimal technology and lack of information dissemination. Umoh et al. (2024) discussed the integration and impact of artificial intelligence (AI) and the Internet of Things (IoT) in smart green building design, finding that AI and IoT improve energy efficiency and optimize building performance, but also identifying implementation challenges and economic implications.

Li et al. (2024) investigated the relationship between artificial intelligence (AI) and Building Information Modeling (BIM) technologies for sustainable buildings in the context of smart cities, emphasizing the role of digitalization in the AEC industry for operational efficiency and urban sustainability. Khan et al. (2023) examined the impact of green knowledge management (GKM) on green technology innovation and sustainability performance in construction firms, showing that GKM has a significant positive impact on green technology innovation and long-term performance. Singla (2024) explored the green building innovation and engineering ecosystem for a sustainable future, focusing on how advanced technologies, environmentally friendly materials, and sustainable practices can mitigate climate change and improve environmental quality.

While these studies have provided valuable insights into green and smart building technologies, significant research gaps remain. Most studies focus on identifying opportunities, challenges, or benefits in general, and reviewing technological developments. A study by Ejidike and Mewomo (2023) highlighted the low adoption of SBT in developing countries, but did not specifically examine the perspectives of stakeholders in academic settings or civil engineering educational institutions. A study by Bungău et al. (2022) also acknowledged low public acceptance and inadequate information dissemination regarding green buildings.

Previous research has tended to be macro-based or focused on specific case studies of implementation without delving deeply into the perceptions, experiences, and strategies adopted by key individuals within educational institutions. This gap

highlights the need for more in-depth qualitative studies to holistically understand how green and smart building technologies are perceived, integrated, and taught within the context of higher education institutions in the Medan area. This study will attempt to fill this gap in the literature by exploring deeper perspectives from civil engineering academics on this issue.

The novelty of this research lies in its specific qualitative approach to analyzing the perceptions, challenges, and strategies for developing green and smart building technologies in universities in the Medan area. This approach allows researchers to understand nuances and complexities that might not be revealed through quantitative studies. Specifically, this research will explore how the experiences of lecturers, students, and practitioners in academic settings influence the adoption and innovation of sustainable construction technologies, providing a richer and more contextualized view of the topic.

This research is crucial given the growing urgency of transitioning to sustainable construction amidst global environmental challenges. Identifying and understanding perceptions and strategies for developing green and smart building technologies in higher education is a fundamental step. This understanding can form the basis for formulating more effective educational policies. These policies are essential for producing competent graduates in the field of sustainable construction, in line with the National Energy General Plan (RUEN), which targets 17% energy efficiency by 2025.

The results of this study can significantly contribute to the development of civil engineering curricula. It can also encourage innovation in construction practices in the Medan area and support national efforts to achieve sustainable development targets. This research is expected to be a valuable source of information for academics, practitioners, and policymakers in encouraging the adoption of sustainable construction innovations in Indonesia.

The phenomenon of global climate change is driving the construction sector to undergo radical transformation, given its significant contribution to carbon emissions and resource consumption. Despite its significant benefits, the adoption of smart building technologies remains challenging in developing countries (Chen et al., 2022). Responding to this climate crisis demands sustainable innovation that

not only reduces the ecological footprint but also improves the quality of human life through a healthier and more resilient built environment (Husainy et al., 2024).

Regionally, in Southeast Asia, rapid economic growth is often accompanied by increased infrastructure and intensive property development. This puts significant pressure on the natural environment and requires innovative and sustainable construction solutions. Several countries in the region, including Indonesia, have begun to demonstrate their commitment to integrating green and smart building principles into their national development plans. However, implementation still faces various challenges, including limited technological capacity and market understanding.

In the local context, Medan, as one of Indonesia's largest metropolitan cities, is experiencing rapid urbanization and development. The increase in construction activity in Medan creates an urgent need to adopt more sustainable practices. The development of infrastructure and new buildings in the city should ideally be balanced with the application of green and smart building technologies to reduce environmental burdens and improve operational efficiency. A comprehensive overview of how universities in Medan contribute to this context is lacking.

Another study by Li et al. (2024) highlighted the importance of integrating artificial intelligence (AI) and Building Information Modeling (BIM) to promote sustainability in the urban construction sector. Their findings indicate that digitalization plays a crucial role in achieving operational efficiency and supporting broader built environment sustainability. The implementation of these technologies still requires adaptation and capacity building, particularly in developing countries. Previous research by Nilimaa (2023) specifically addressed trends and opportunities in sustainable concrete construction, emphasizing that environmentally friendly practices are key to mitigating the industry's ecological impact. Nilimaa (2023) also identified that technical, economic, and social challenges often hinder the full adoption of more sustainable concrete construction methods.

Ejidike and Mewomo (2023) argue that although intelligent building technology (SBT) offers significant benefits such as energy efficiency and operational cost savings, its adoption rate in developing countries remains relatively

low. They identify a lack of understanding and awareness as key barriers. Rani (2024) evaluates the green building concept and acknowledges that suboptimal technology and a lack of information dissemination contribute to low public acceptance. This indicates a gap between the technology's potential and its actual implementation on the ground.

Previous research, such as that conducted by Gallo et al. on prefabrication, and Umoh et al. on AI and IoT, tends to focus on the technical performance or general benefits of the technology. These studies lack specific exploration of how perceptions, challenges, and development strategies for these technologies are internalized in the curriculum and educational practices of civil engineering universities. This gap indicates an urgent need to understand the perspectives of academics and students who are potential agents of change in the construction sector, particularly in areas with unique development characteristics like Medan.

A clearly identified research gap is the lack of in-depth qualitative studies that explicitly explore the perceptions, experiences, and strategies for developing green and smart building technologies from the perspective of stakeholders in academic settings, particularly in civil engineering universities in Medan. Existing studies tend to be general, macro, or focus on technical aspects and economic benefits, without providing insight into implementation challenges at the higher education level. This research aims to fill this gap by focusing on the local context of Medan, providing a more comprehensive picture of how these sustainable innovations can be effectively integrated into civil engineering education.

This research is highly urgent given the central role of universities in developing future professionals and driving innovation in the construction sector. A deeper understanding of how green and smart building technologies are perceived and taught in universities will provide a strong foundation for developing relevant and practical curricula. This is crucial for producing graduates who not only master the latest technologies but also demonstrate an awareness and commitment to the principles of sustainable development, in line with growing global and national demands.

Data

source:tempo.co; antaranews.com; katadata.co.id; kompas.com; dml.or.id; aki.or.id.

1.2 Problem Identification

The problem identification in this study focuses on the gap between the potential and implementation of green and smart building technologies in the context of sustainable construction. Global climate change and natural resource scarcity are key drivers of the need for innovation in the construction sector. Sustainable development, encompassing environmental, economic, and social aspects, is imperative to mitigate negative impacts on the planet. The implementation of green and smart building technologies can be a transformative solution, but various challenges hinder their widespread adoption. It is crucial to specifically identify these barriers to formulate effective solutions.

This research identifies several key issues related to the adoption of green and smart building technologies as innovations in sustainable construction. First, understanding and awareness of the long-term benefits and the feasibility of initial investments in green and smart building technologies remains limited among construction industry stakeholders. Many tend to view the high initial costs without fully understanding the potential energy and operational savings. Expanding information on the economic and environmental benefits is crucial to encourage wider adoption.

Second, the lack of a strong regulatory framework and incentive policies from the government pose a significant barrier to the development and implementation of this technology. Without regulatory pressure or fiscal incentives, construction industry players are often reluctant to shift from cheaper and more established conventional methods. Developing supportive policies, such as subsidies or streamlined permitting, could accelerate the transition to more sustainable construction practices.

Third, integrating smart building technologies with green building principles still faces technical complexity and a lack of uniform standards. Various smart systems, such as automated energy management or environmental sensors, require strong interoperability to achieve maximum efficiency. Platform and protocol differences between vendors often hinder seamless integration, hindering the optimal performance of both approaches.

Fourth, the availability of human resources with specialized expertise in designing, constructing, and managing green and smart buildings remains limited in the construction industry. Developing skills in this area requires a relevant educational curriculum and training to produce competent experts. Without a trained workforce, the effective implementation of these innovative technologies will be difficult.

Fifth, the relatively high initial investment costs for green and smart building technologies are often a major financial barrier for developers, especially on projects with limited budgets. While the potential for long-term savings is significant, these initial costs can be prohibitive for small and medium-sized companies. Finding innovative financing models or financial support schemes can help overcome this barrier and encourage greater investment.

Sixth, data and case studies on the long-term effectiveness and return on investment (ROI) of green and smart building projects in Indonesia, particularly in Medan, are still scarce. This lack of robust empirical evidence makes it difficult for stakeholders to make informed investment decisions. Further research is needed to document successful implementation and provide a clear picture of the positive impacts of this technology.

1.3 Problem Formulation

Issues of construction sustainability and the environmental impact of building construction are driving technological innovation. Green and smart building technologies are emerging as transformative solutions to address these challenges, offering new approaches to infrastructure planning, design, operation, and maintenance. The implementation of these technologies is expected to create a more energy-efficient, ecologically sustainable, and responsive built environment to occupant needs (Gallo et al., 2021). The adoption process and specific impacts of these technologies in the context of sustainable construction require a deeper understanding.

The following is the formulation of the problem in this research:

1. How are green building technologies implemented as innovations in sustainable construction?

2. How is smart building technology applied as an innovation in sustainable construction?
3. What are the main challenges faced in implementing green and smart building technologies as sustainable construction innovations?
4. What strategies can be proposed to increase the adoption of green and smart building technologies in the construction sector?

1.4 Research Objectives

This study is designed to explore various aspects related to the adoption of this technology, from its application to improvement strategies in the construction sector. The information obtained is expected to provide comprehensive guidance for stakeholders in realizing sustainable development. Understanding the local context, particularly in Medan, is also a focus to ensure the resulting solutions are relevant. Aligning these objectives with the established research problem is a crucial aspect of the research. Each objective specifically addresses the questions posed in the research problem formulation.

The following are the objectives of this research:

1. Analyzing the implementation of green building technology as an innovation in sustainable construction.
2. Identifying the application of smart building technology as an innovation in sustainable construction.
3. Explores the key challenges faced in implementing green and smart building technologies as sustainable construction innovations.
4. Formulate strategies that can be proposed to increase the adoption of green and smart building technologies in the construction sector.

1.5 Benefits of Research

This research has significant theoretical and practical benefits for the development of sustainable construction science and practice. The theoretical benefits focus on enriching the body of knowledge in civil engineering, particularly regarding the implementation of green and smart building technologies as sustainable construction innovations. Practical benefits are intended for various

stakeholders involved in promoting sustainability in the construction sector in Indonesia.

This study is expected to provide a substantive contribution to enriching the scientific literature on green and smart building technologies, particularly in developing urban contexts. A thorough understanding of the implementation of this innovation can form the basis for developing a new theoretical framework that integrates aspects of environmental sustainability, energy efficiency, and technological sophistication in building design and operation. The findings of this study also have the potential to serve as an initial reference for further studies focusing on evaluating the long-term impacts of these technologies on the environment and society. This research contributes to the development of civil engineering through an in-depth qualitative approach.

This research yields a number of concrete benefits for various parties involved in the sustainable construction industry:

1. For the Construction Industry: This research can provide practical guidance for developers, contractors, and consultants in adopting green and smart building technologies. Information on best practices, challenges, and innovative solutions will help construction companies improve their projects' sustainability performance, reduce environmental impact, and meet global standards.
2. For Government and Regulators: The results of this study are expected to provide valuable input for the formulation of policies and regulations that support the implementation of sustainable construction. Recommendations emerging from this research can be used to develop more effective incentives, certification standards, and building guidelines to encourage the adoption of environmentally friendly technologies in the property sector.
3. For Academics and Students: This research provides relevant empirical data and qualitative analysis as teaching materials, references, and inspiration for further research. Civil engineering students can gain a deeper understanding of innovation trends in sustainable construction, preparing them for future challenges in the industry.

4. For the General Public: Increasing understanding and implementation of green and smart buildings will ultimately have a positive impact on people's quality of life. More energy-efficient and environmentally friendly buildings will create healthier, more comfortable living and working environments, and contribute to broader climate change mitigation.

1.6 Problem Definition

The purpose of this research is to clarify the scope of the study to maintain focus and allow for more in-depth analysis. This limitation is crucial to ensure that the research does not extend beyond the scope or available resources, thus producing relevant and measurable findings. The research will focus on specific aspects of the implementation of green and smart building technologies within the context of sustainable construction in the Medan region. This limitation will allow for a more focused investigation of the key issues to be addressed, in accordance with the established research problem formulation. It also helps maintain consistency in the methodology and interpretation of the data collected during the research process. The limitation of the research problem serves as an important foundation for maintaining the validity and reliability of this qualitative study.

This research is limited by several main aspects, including:

1. The focus of this research is only to examine the implementation of green and smart building technology as an innovation in sustainable construction.
2. The aspects studied include perceptions, challenges, and strategies for adopting green and smart building technologies.
3. The location of this research is limited to construction projects that apply green and smart building technologies in the Medan area.
4. The research subjects are stakeholders in the construction industry in Medan, such as architects, engineers, developers, and related academics.
5. This research uses a qualitative approach with data collection methods through in-depth interviews and documentation studies.
6. The research period will take place during the 2026/2027 academic year, starting from September 2026 to May 2027.

CHAPTER II LITERATURE REVIEW

2.1 Theoretical Basis

2.1.1 Green Building Technology

The integration of environmental science and technology into construction creates green building technology, resulting in sustainable and environmentally friendly buildings (Chukwu et al., 2022). This technology focuses on minimizing a building's negative impact on the natural environment throughout its life cycle. Green buildings require efficient resource use, from planning, design, construction, operation, maintenance, renovation, and demolition. This concept contributes to reduced consumption of energy, water, and other natural resources. The ultimate goal is to create a healthy and comfortable built environment for occupants, reducing carbon footprints and greenhouse gas emissions. Green buildings should be part of sustainable environmental development (Bungău et al., 2022).

The dimensions of green building technology encompass several important aspects that need to be considered in its implementation. These aspects include energy efficiency, water efficiency, waste reduction, the use of environmentally friendly materials, and improving indoor environmental quality (Chen et al., 2022). Green building materials, such as recycled materials, bio-based products, and high-performance insulation technologies, play a central role in advancing sustainable architecture (Iwuanyanwu et al., 2024). The use of these materials not only reduces the environmental impact of construction but also enhances the overall sustainability of the building. Considering these dimensions helps design, construct, and operate buildings with minimal impact on the planet.

Various factors influence the adoption of green building technologies, involving multiple stakeholders. High initial costs are often a barrier, despite the potential for long-term savings through energy and operational efficiencies. Concerns about the performance and durability of green materials, as well as supply chain issues, also hinder the widespread adoption of these technologies. Lack of public awareness and knowledge about the benefits of green buildings is a significant challenge that needs to be addressed. Government, industry, and

academia have a role to play in promoting sustainable construction practices through interdisciplinary collaboration and ongoing research (P. & T., 2023).

The success of green building technologies can be measured through various quantitative and qualitative parameters. These parameters include reduced energy consumption, reduced clean water use, the percentage of recycled materials used, and improved indoor air quality. Green building certification from relevant accreditation bodies, such as the Green Building Council, can also serve as a formal indicator. Algae technology, for example, offers a promising strategy for green building practices; it reduces CO₂ emissions and converts wastewater into bioenergy, demonstrating significant economic and environmental potential (Çelekli et al., 2024). Measuring these indicators allows for objective evaluation of the impact and effectiveness of green building technology implementation.

This research analyzes green building technology as a transformative innovation in sustainable construction. It focuses on a thorough understanding of its implementation, including material selection, passive design, and the integration of renewable energy sources. Sustainable buildings, including green buildings, aim to use energy, water, and other resources in a balanced manner without overexploitation (Meena et al., 2022). This research aims to explore how this technology can be optimized in Medan and identify strategies to overcome emerging challenges. The results are expected to provide relevant recommendations for the development of more environmentally friendly and efficient construction.

2.1.2 Smart Building Technology

Smart building technology refers to the integration of advanced systems capable of automatically managing and optimizing building functions. This concept involves the use of sensors, actuators, and communication networks to collect building operational data and then use that data to improve energy efficiency, occupant comfort, and security (Apriyanto & Hidayat, 2025). Smart buildings are a crucial component of the technical infrastructure of smart cities, where resources are used more efficiently and innovatively (Radziejowska & Sobotka, 2021). The application of smart building technology is becoming a new trend in development, attracting interest compared to conventional buildings (Ejidike & Mewomo, 2023).

The development of intelligent building technology is supported by rapid advances in information and communication technologies, such as the Internet of Things (IoT) and Artificial Intelligence (AI). The integration of AI and IoT improves energy efficiency, optimizes building performance, and contributes to environmental sustainability (Umoh et al., 2024). This technology enables buildings to learn from occupant usage patterns and environmental conditions. This allows for real-time adjustments to lighting, heating, ventilation, and air conditioning systems. Through this optimization, intelligent building technology can substantially reduce energy consumption and greenhouse gas emissions (Rodríguez-Gracia et al., 2023). AI also has significant potential to improve structural stability and minimize negative ecological impacts on the environment and society.

The benefits of adopting smart building technologies in the construction industry are diverse, especially in developing countries. This paper aims to identify the inherent benefits of adopting smart building technologies (SBT) in the construction industry (Ejidike & Mewomo, 2023). These technologies also create new job opportunities and improve the overall quality of life. The application of smart construction technologies, such as parametric design combined with BIM, big data, and intelligent decision-making systems, supports the implementation of green buildings from the initial design stage to optimized outcomes (Peng, 2025). Challenges such as high initial costs, interoperability issues, and limited user awareness still need to be addressed for wider adoption.

The performance of intelligent buildings can be measured through energy efficiency, adaptive response to changing environmental conditions, and occupant comfort and safety. Real-time monitoring of energy consumption, indoor air quality, and security systems are examples of key indicators. This technology supports sustainability goals by providing data that enables continuous optimization. AI applications in intelligent buildings, for example, can rationally optimize building functions, positively impact structural stability, and minimize ecological impact.

This research seeks to identify how smart building technologies are applied as innovations in sustainable construction. The study will explore the role of IoT,

AI, and automation systems in improving operational efficiency and building sustainability. The implementation of Building Information Modeling (BIM) as a critical tool for the construction industry is also part of the effort to create sustainable smart cities (Chen et al., 2022). Interdisciplinary collaboration, regulatory incentives, and user-centric solutions are considered crucial for successful implementation. An in-depth analysis of its implementation and impact will provide a comprehensive understanding for stakeholders.

2.1.3 Sustainable Construction

Sustainable construction is a comprehensive approach to development that aims to meet the needs of the present without compromising the ability of future generations to meet their own needs. This concept involves considering environmental, economic, and social aspects at every stage of a construction project, from planning, design, construction, operation, maintenance, and end-of-life (Deutz et al., 2024). A shift in perspective in development projects toward environmentally friendly and sustainable development has occurred (Tauheed et al., 2021). The main objectives are to reduce the construction industry's negative impact on the environment, optimize resource use, and improve people's quality of life. This encompasses climate change mitigation, natural resource conservation, and the promotion of social welfare.

The principles of sustainable construction include resource efficiency, reduced environmental impact, improved human health and comfort, and cost efficiency throughout the building's life cycle (Kibert, 2024). The use of environmentally friendly and high-performance materials, designs that optimize natural lighting and ventilation, and the integration of renewable energy systems are some examples of key practices. Sustainable urban infrastructure, including innovations in green building technologies and urban planning, is becoming a crucial component of urban development (Singla, 2024). Challenges such as rapid urbanization, climate change, and resource depletion are urging a paradigm shift toward sustainability in urban infrastructure (Rani, 2024).

Implementing sustainable construction faces various challenges, including high initial costs, a lack of clear standards and regulations, and resistance to change from conventional practices (Bungău et al., 2022). Innovations in green and smart

building technologies offer promising solutions to overcome these barriers. Retrofitting existing buildings for sustainability is a crucial strategy to address the environmental impacts of the built environment, enhance economic benefits, and improve social well-being. Technical, financial, regulatory, and logistical barriers need to be addressed for wider adoption. Collaboration between government, industry, and academia is crucial to encourage the adoption of sustainable construction practices and facilitate innovation (Husainy et al., 2024).

The benefits of sustainable construction include long-term operational cost savings through energy and water efficiency, increased property value, and positive contributions to occupant health and productivity. Green buildings offer advantages in terms of energy consumption and emissions, lower maintenance and operational costs, and improved health and productivity (Meena et al., 2022). From an environmental perspective, sustainable construction helps reduce greenhouse gas emissions, preserve ecosystems, and mitigate resource depletion. Technological innovations, such as algae technology, also demonstrate economic and environmental potential in reducing CO₂ emissions and generating bioenergy for building needs (Çelekli et al., 2024).

This study examines sustainable construction as a key framework for green and smart building technology innovation. The framework provides context for how these technologies can be integrated to achieve broader development goals. The concept of Construction 5.0 has emerged as the next frontier in construction practice, characterized by the integration of advanced technologies with human-centered approaches, sustainable practices, and resilience considerations to construct smart, future-ready buildings (Yitmen et al., 2024). An investigation into the challenges and strategies for adopting these technologies will provide practical guidance for stakeholders in realizing a more resilient and efficient built environment in Medan.

2.1.4 Innovation in Construction

Innovation in construction refers to the introduction and application of new ideas, processes, technologies, or materials that result in improvements in the efficiency, sustainability, performance, or safety of construction projects. This innovation can include digital technologies such as Building Information Modeling

(BIM) and Artificial Intelligence (AI), advanced building materials, new construction methods, and adaptive design approaches (Li et al., 2024). Advanced technologies, environmentally friendly materials, and sustainable practices play a crucial role in mitigating climate change and improving environmental quality (Husainy et al., 2024). The goal of innovation is to address the industry's evolving challenges, including climate change and resource scarcity.

Diffusion of innovation, as explained by Rogers (2003), is the process by which an innovation is communicated through specific channels over time among members of a social system. This concept is relevant in understanding how green and smart building technologies spread and are adopted in the construction sector. The adoption process of new technologies is influenced by factors such as the characteristics of the innovation itself, the communication channel, time, and the nature of the social system (Rogers, 2003). Understanding the dynamics of diffusion helps identify effective strategies to encourage the adoption of sustainable innovations.

Green knowledge management is becoming increasingly important as a key driver of green technology innovation and sustainable performance in construction organizations. Green knowledge management positively influences green technology innovation and long-term performance (Khan et al., 2023). This includes the collection, dissemination, and utilization of knowledge related to environmentally friendly practices. Artificial intelligence (AI) also has a significant impact on the relationship between green knowledge management and green human capital, demonstrating AI's significant potential in facilitating sustainable innovation (Khan et al., 2023).

Types of innovation in construction can be categorized into product, process, and organizational innovation. Product innovation includes the development of new building materials or component systems that are more efficient and sustainable. Innovations such as self-healing concrete, 3D-printed concrete, photocatalytic concrete, electric motors, and carbon capture, utilization, and storage principles are discussed in this review, highlighting their potential to improve the sustainability of construction practices (Nilimaa, 2023). Organizational innovation focuses on management structures, collaboration between stakeholders,

and policies that support sustainable practices. The adoption of technologies such as BIM and AI, which enable improvements in operational efficiency and sustainability, illustrates the interconnectedness of process and product innovation in the context of smart cities.

This study examines innovation as a process driving the adoption of green and smart building technologies in sustainable construction. A qualitative approach allows for an in-depth exploration of how these innovations are perceived, implemented, and the challenges faced. Advances in green building technologies have grown substantially due to the environmental, economic, and social benefits they offer (Meena et al., 2022). This study will identify the mechanisms that support or hinder innovation and formulate strategies that can enhance the diffusion and adoption of these innovative technologies in the Medan region.

2.1.5 Circular Economy in Sustainable Construction

The concept of a circular economy offers a transformative framework for sustainable construction, shifting from a model

2.2 Theoretical Framework

2.2.1 Research Theoretical Framework

This research is conceptually grounded in a theoretical framework that integrates diverse perspectives and understands the phenomenon of green and smart building technology as an innovation that supports sustainable construction. This approach is useful for identifying the contribution of technology implementation to sustainable development, while also identifying challenges and strategies to overcome them. This research arises from the urgent need to improve environmental, economic, and social sustainability in the construction industry (Gallo et al., 2021). This framework focuses on the interaction between sustainability concepts, technological innovation, and urban construction practices, as global climate change and natural resource scarcity are driving the construction sector to adopt more environmentally friendly and efficient approaches (Singla, 2024; Rani, 2024). The researchers developed this theoretical framework to provide a coherent analytical structure to address the research problem. The application of this framework helps identify gaps in the literature that can be filled by research, in

line with guidelines for developing theoretical frameworks that emphasize the importance of theory as a lens for analyzing the phenomena under study (Bingham et al., 2024).

The use of this framework ensures that data interpretation is scientifically sound and relevant, and provides direction for researchers in collecting and analyzing qualitative data. The theoretical framework helps ensure that research findings are generalizable and contribute to broader knowledge in civil engineering (Booth et al., 2024), while in-depth qualitative analysis will focus on stakeholders' perceptions and experiences in implementing this technology. This research fundamentally aims to explore how technology can support sustainable development goals, and conceptualizing this relationship is crucial for formulating strategies to increase technology adoption in the construction sector. This framework will highlight how various dimensions of sustainability, including energy efficiency, resource management, and socioeconomic impacts, interact with green and smart building technologies. This framework provides a strong foundation for understanding the complexities of innovation in the construction sector, including optimizing building performance through technology integration as a primary focus (Umoh et al., 2024; Apriyanto & Hidayat, 2025). Understanding the interplay between technology and sustainability is crucial for guiding policy recommendations.

This approach allows researchers to identify key factors influencing the success of technology implementation in Medan, and the framework will also consider how these innovations can be adapted to the local context. This framework provides a basis for structured and in-depth analysis in qualitative research, as the implementation of green and smart building technologies in the construction sector requires a systematic understanding. This concept supports the analysis of challenges and opportunities. The integration of relevant theories helps explain the dynamics of technology adoption, and this framework will guide the process of data interpretation and conclusion drawing. The theories used in this research relate to innovation, technology adoption, and sustainable development, and the application of these theories provides a solid foundation for the analysis. Each element of this framework is designed to contribute to a better understanding of the research topic,

as qualitative analysis requires a flexible yet structured framework to extract meaning from rich data.

Researchers will use this framework to guide exploration, help focus research questions and guide data collection, and analyze informants' perceptions and experiences. The theoretical framework helps explain how technological innovations interact with social and economic contexts, and this approach allows researchers to identify significant patterns in the data. This understanding is crucial for developing relevant recommendations. Sustainability is a multidimensional concept that must be considered from multiple perspectives, ensuring all relevant aspects are taken into account (Bungău et al., 2022). This framework supports in-depth analysis of complex issues, and the integration of multiple theories will enrich research insights. This theoretical framework will provide a clear direction for qualitative research (Creswell et al., 2018) and help ensure that all findings are relevant and structured.

2.2.2 Integration of Innovation Theory

This research will integrate theories related to technological innovation within the context of sustainable construction and adaptation in urban environments. The framework will specifically discuss how green and smart building technologies provide solutions to environmental challenges and support an analysis of their positive impacts. Strategies to increase the adoption of these technologies will also be discussed, and an in-depth analysis of the factors influencing adoption is a key component of the framework. A discussion of innovation theory will explain how new technologies are accepted and disseminated within the construction industry (Mas'odi, 2024), an aspect crucial for understanding the dynamics of change. Technology adoption theory will provide insight into the acceptance process, including factors that motivate or hinder its implementation. The framework will also consider sustainable development theory as an umbrella term, ensuring all innovations are oriented toward long-term positive impacts (Meena et al., 2022).

This understanding will help evaluate the effectiveness of the technology, as a theoretical framework in qualitative research serves as a roadmap for understanding and interpreting complex phenomena (Maxwell, 2013). This

approach helps researchers maintain focus while remaining open to new findings emerging from the data. The theory also helps connect the research findings to existing literature, enriching the study's academic contribution. Analysis based on relevant theories will produce more robust and valid findings. This framework will ensure consistency in data interpretation and serve as a basis for developing practical recommendations to increase the adoption of green and smart building technologies. It allows researchers to identify gaps in existing knowledge and contribute to the development of new theories in civil engineering.

This framework will help researchers understand the dynamics of change, and technology integration in the context of sustainable construction will be analyzed in depth. This approach will enable the research to make significant contributions to advancing more innovative and sustainable construction practices. Researchers will ensure that every aspect of the research problem formulation can be addressed through this framework, which is key to the overall success of the research. This theoretical framework explicitly outlines the relationship between technological innovation and sustainable development (Miles et al., 2018). Researchers will use this framework to explore qualitatively, identifying themes and patterns that emerge from the data. A deep understanding of these theories will enable researchers to conduct comprehensive analyses, encompassing technical, economic, social, and environmental dimensions.

This framework serves as a tool for filtering and organizing relevant information. It ensures the research remains focused throughout the process, and a strong theoretical framework enhances the credibility and validity of the research findings. This is crucial for ensuring the trustworthiness of the study's results, and it also provides a basis for comparison with other studies, strengthening the research's position within the broader academic discourse. This theoretical framework is a solid foundation for high-quality research. It helps researchers generate valuable and relevant insights in the context of green and smart building technologies. The process of developing this theoretical framework also involves synthesizing diverse expert perspectives, ensuring the research encompasses a diverse range of relevant perspectives.

This framework will serve as the primary guide for researchers from data collection to interpretation of results and development of recommendations. Alignment between the theoretical framework and the research problem formulation is emphasized, ensuring the research remains focused and relevant to its initial objectives. The integration of relevant theories helps explain the dynamics of technology adoption, and this framework will guide data interpretation and conclusion drawing.

2.2.3 Socio-Economic Dimension

A theoretical framework helps explain how technological innovations interact with social and economic contexts. This approach allows researchers to identify significant patterns in the data, and this understanding is crucial for developing relevant recommendations.

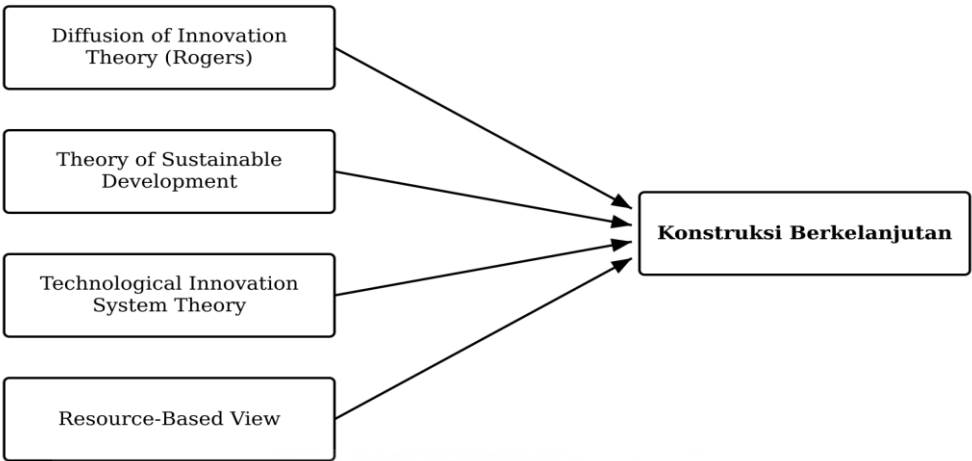
A thorough understanding of these theories will enable researchers to conduct comprehensive analyses. These analyses encompass technical, economic, social, and environmental dimensions, and the framework serves as a tool for filtering and organizing relevant information.

2.2.4 Validity and Comparability

This is crucial to ensuring the credibility of the study's results, and the framework also provides a basis for comparison with other research. This comparison strengthens the research's position within the broader academic discourse, as the theoretical framework provides a solid foundation for high-quality research.

This framework will also consider sustainability aspects from a social and economic perspective, and this approach is crucial for generating comprehensive recommendations. This approach helps identify the potential impacts of technology on societal well-being, as a solid theoretical framework allows researchers to address the complexities of technological innovation in an ever-changing context. This framework will serve as a basis for careful interpretation of the collected qualitative data.

Figure 2.1 Theoretical Framework



Teori-teori yang mendasari Konstruksi Berkelanjutan

2.3 Previous Research

Previous research on green and smart building technology innovations in sustainable construction has shown significant attention to mitigating the environmental impacts of the construction sector. Numerous studies have highlighted the importance of adopting these technologies to achieve energy efficiency, reduce greenhouse gas emissions, and enhance overall sustainability in the built environment. Numerous studies have explored the benefits, challenges, and implementation strategies of these technologies from various perspectives, ranging from construction materials to intelligent system integration. These studies have also identified knowledge gaps that need to be addressed to support broader and more effective adoption, particularly in diverse contexts. A thorough understanding of these findings is crucial for identifying areas requiring further exploration; the integration of technology and sustainability aspects has been a key focus of these studies.

Table 2.1 Previous Research

Table 2.1Previous Research

No	Name (Year)	Title	Results	Gap
1	P. & T. (2023)	Influence of consumer motivations and perception on the adoption of smart,	Consumer moral and ethical values influence decisions to adopt	A deeper analysis is needed regarding strategies to overcome adoption challenges.

No	Name (Year)	Title	Results	Gap
		green, and sustainable building materials	sustainable construction materials	
2	Tauheed et al. (2021)	Building A Green Commercial Complex Using Green Building Materials And Using Sustainable And Smart Resources- A Case Study	Green buildings with the latest material and technology modifications reduce environmental damage.	Not yet focused on the specific implementation challenges of smart technologies
3	Silva et al. (2023)	Sustainable, green, or smart? Pathways for energy-efficient healthcare buildings	Energy use and GHG emissions of buildings are a major concern; both passive and active measures are needed.	Research limitations on small-scale health buildings
4	Chen et al. (2022)	Construction 4.0, Industry 4.0, and Building Information Modeling (Bim) for Sustainable Building Development within the Smart City	Integration of Construction 4.0, Industry 4.0, BIM is crucial for sustainable smart city development	Further exploration of multidisciplinary integration in specific contexts is needed.
5	Yitmen et al. (2024)	Facilitating Construction 5.0 for smart, sustainable and resilient buildings: opportunities and challenges for implementation	Adoption of human-centered technologies, resilience, and sustainability facilitates Construction 5.0	There is no comprehensive perspective on the opportunities and challenges of facilitation.
6	Ejidike & Mewomo (2023)	Benefits of adopting smart building technologies in building construction of developing countries: review of literature	Smart building technologies offer energy efficiency, cost-effective maintenance, and job creation.	Low attention of construction professionals in developing countries towards adoption
7	Bungău et al. (2022)	Green Buildings as a Necessity for Sustainable Environmental Development: Dilemmas and Challenges	Green building development is important but is hampered by technology optimization, ROI, and information dissemination.	Further clarification is needed on the principles and applications of green buildings.
8	Kim et al. (2022)	Design and Implementation of Smart Buildings: A Review of Current Research Trends	Building energy technology plays an important role in improving the sustainability of the built environment.	Limitations of the review on current research trends in smart energy system implementation

No	Name (Year)	Title	Results	Gap
9	Peng (2025)	Application of Smart Construction Technology in Green Building Design	Smart construction technology supports green building design through BIM, big data, and AI.	Need deeper analysis on result verification and continuous optimization
10	Iwuanyanwu et al. (2024)	The role of green building materials in sustainable architecture: Innovations, challenges, and future trends	Green building materials are important for reducing environmental impact, but face cost and performance challenges.	There is no comprehensive solution to address the barriers to widespread adoption of green materials.

Previous studies have shown a general agreement on the importance of green and smart building technology innovation in achieving sustainable construction. Tauheed et al. highlighted how modifications to materials and technology can reduce environmental damage. Peng (2025) added that smart construction technologies, including BIM, big data, and AI, significantly support green building design. This understanding of benefits is reinforced by Ejidike and Mewomo (2023), who identified energy efficiency, operational cost-effectiveness, and job creation as advantages of adopting smart building technologies, particularly in developing countries.

Several studies also explore broader technology integration in the context of sustainable development. Chen et al. (2022) emphasize the role of Construction 4.0, Industry 4.0, and BIM as central elements for sustainable smart city development. Yitmen et al. (2024) further discuss Construction 5.

0, outlines the opportunities and challenges in facilitating smart, sustainable, and resilient buildings through the adoption of human-centered technologies. Material aspects are also a focus; Iwuanyanwu et al. (2024) discuss the role of green building materials in sustainable architecture, including innovations such as recycled materials and smart materials that offer improved durability.

The implementation of these technologies often faces several challenges. P. & T. highlighted the barriers to the use of smart, green, and sustainable building materials influenced by consumer perceptions and motivations. Bungău et al. (2022) identified that public acceptance of green buildings remains low due to

technology optimization, low return on investment (ROI), and lack of information dissemination. Silva et al. (2023) reviewed the literature to promote energy-efficient and comfortable healthcare buildings, noting the specific challenges posed by round-the-clock operation and stringent hygiene standards. Husainy et al. (2024) reviewed technological advances in energy and environmental systems in buildings, which have played a significant role in improving the energy sustainability of the built environment.

This research seeks to fill this gap by specifically exploring the implementation of green and smart building technologies in sustainable construction, with a focus on challenges and strategies for increasing adoption, particularly in the Medan area. Unlike previous studies, which tend to be general or focused on specific technical aspects, this research will analyze the perceptions and experiences of local stakeholders. It will also identify constraints that may be unique to specific geographic and socioeconomic contexts and formulate relevant and implementable strategies to encourage broader adoption.

The consumer perspective plays a vital role in the adoption of green and smart building technologies. The final decision often rests with them or developers responding to market preferences. P. & T. (2023) highlighted that consumers' personal values and moral ethics, with a high average score (4.25), significantly influence their decisions in selecting construction materials. Awareness of environmental impacts and social responsibility are strong drivers behind the desire to adopt sustainable materials. Radziejowska & Sobotka (2021) emphasized that the smart city concept, as an evolution of various previous sustainable development ideas, requires a deep understanding of how these initiatives are accepted and integrated by society.

The integration of information and communication technology (ICT) is a fundamental element in smart buildings. ICT acts as the backbone, enabling system efficiency and operationalization. Kim et al. (2022) reviewed technological advances in energy and environmental systems in buildings, which have played a significant role in improving the energy sustainability of the built environment. The use of ICT also supports the Construction 4.0 and Industry 4.0 approaches, as outlined by Li et al. (2024), which simultaneously utilize Building Information

Modeling (BIM) for the development of sustainable smart cities. This synergy enables more efficient and integrated building planning, design, and operation, reducing waste and improving overall energy performance.

Despite the clear benefits, the adoption of green and smart buildings still faces various complex obstacles, including consumer perceptions and motivations, as demonstrated by P. & T. (2023). The study found a significant positive correlation ($r = 0.629$, $p = 0.001$) between adoption challenges and influencing factors, underscoring the need for a comprehensive strategy. Bungău et al. added that low public acceptance is often caused by a lack of proper technology optimization, suboptimal return on investment (ROI), and inadequate dissemination of information regarding long-term benefits. Strategies to increase adoption should include extensive public education, demonstration of successful pilot projects, and supportive financial and regulatory incentives to accelerate the transition to more sustainable construction practices.

2.4 Framework of Thinking

Global climate change and natural resource scarcity have pushed the construction sector to adopt a more sustainable development approach. The building and construction sector significantly impacts energy consumption and greenhouse gas emissions, necessitating strategic interventions (Gallo et al., 2021). Sustainable development in construction is imperative to mitigate negative environmental, economic, and social impacts. Smart cities offer the most desirable urban development conditions today, embracing the concept of sustainable development at its core (Chen et al., 2022). This creates a crucial foundation for innovation in construction practices to achieve sustainability goals.

This research focuses on innovations in green and smart building technologies in response to the need for sustainable construction. Green building technology is a combination of environmental science and technology that aims to create environmentally friendly buildings and reduce their negative impacts throughout their life cycle (Chukwu et al., 2022). This technology focuses on the balanced use of energy, water, and other resources without overexploitation to improve environmental conditions (Meena et al., 2022). Green buildings contribute

to mitigating environmental impacts through energy-efficient design and the integration of renewable energy sources, improving the quality of life for urban dwellers (Singla, 2024; Rani, 2024).

Innovations in green building materials play a crucial role in sustainable architecture. These materials contribute significantly to reducing the environmental impact of construction and improving the overall sustainability of buildings (Iwuanyanwu et al., 2024). The use of green building materials and the use of sustainable resources in the construction of commercial complexes has demonstrated a shift in perspective towards environmentally friendly and sustainable development (Tauheed et al., 2021). Green buildings, as an implementation of the concept of sustainable development, have many advantages, although public acceptance is still low due to the need for technology optimization and low returns on investment (Bungău et al., 2022).

Smart building technology offers a promising approach to improving energy efficiency. This technology leverages Internet of Things (IoT)-based sensors, adaptive systems, and real-time monitoring for significant energy optimization in green buildings (Apriyanto & Hidayat, 2025). The integration of artificial intelligence (AI) and IoT significantly improves energy efficiency, optimizes building performance, and contributes to sustainability (Umoh et al., 2024). Smart building technology offers benefits such as efficient energy consumption, reduced maintenance and operational costs, and job creation, which have attracted widespread attention thanks to the digitalization of the construction industry (Ejidike & Mewomo, 2023).

Research on advances in building energy technology has also explored energy management systems, renewable energy applications, and advanced smart technologies for optimal functionality and energy-saving performance (Kim et al., 2022). The adoption of smart construction technologies, such as parametric design combined with BIM, big data, and intelligent decision-making systems, supports green building design from the initial stages through verification and optimization (Peng, 2025). The integration of green and smart buildings with artificial intelligence techniques has great potential to ensure better structural stability and minimize negative ecological impacts.

The implementation of green and smart building technologies faces several crucial challenges. High initial costs, interoperability issues between systems, and lack of user awareness are major barriers to integrating smart technologies into green building concepts (Apriyanto & Hidayat, 2025). Consumer perceptions and motivations, as well as the challenges faced, influence the widespread adoption of smart, green, and sustainable building materials in the construction industry. Technical, financial, regulatory, and logistical constraints also pose obstacles to retrofitting existing buildings for sustainability (Iwuanyanwu et al., 2024).

This strategy for increasing technology adoption demands interdisciplinary collaboration, regulatory incentives, and user-centric solutions to ensure successful implementation (Apriyanto & Hidayat, 2025). The role of green knowledge management is a key driver of green technology innovation and sustainable performance in construction companies (Khan et al., 2023). The use of artificial intelligence (AI) and Building Information Modeling (BIM) is also key in helping designers make sustainable decisions at the building and city levels. To address these challenges, this study will analyze the implementation, challenges, and relevant strategies in the specific context of Medan, as a guide for stakeholders.

The following is the framework for this research:

2.4.1 Main Problems

The issues of global climate change and scarcity of natural resources have triggered an urgent need for sustainable development in the construction sector.

2.4.2 Technological Innovation

Green Building Technology and Smart Building Technology are present as transformative solutions to overcome the negative impacts of conventional construction.

2.4.3 Technology Implementation (Problem Formulation 1 & 2)

Implementation of Green Building Technology and Smart Building Technology as innovations in sustainable construction in Medan.

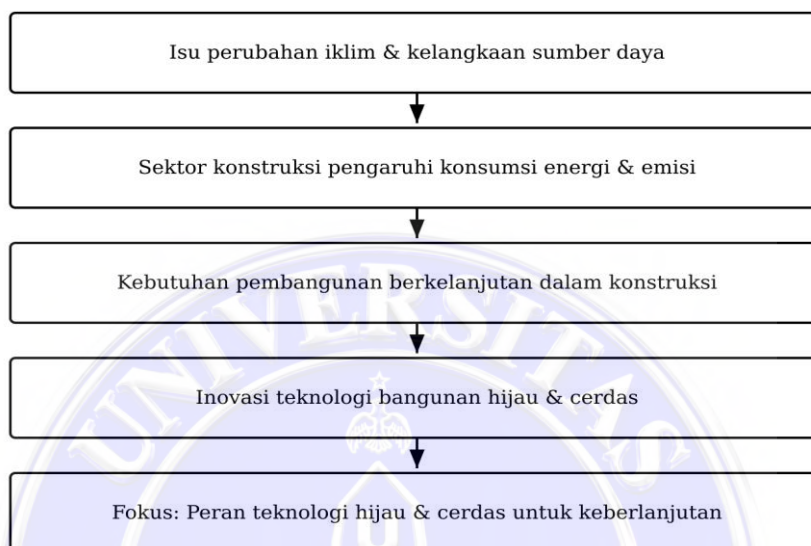
2.4.4 Implementation Challenges (Problem Formulation 3)

The main obstacles faced in implementing these two technologies in the Medan construction sector.

2.4.5 Adoption Enhancement Strategy (Problem Formulation 4)

Proposed strategies to encourage wider adoption of Green Building Technology and Smart Building Technology in Medan's construction sector.

Figure 2.2 Framework of thinking



CHAPTER III METHODOLOGY

3.1 Types & Approaches

A qualitative approach offers the advantage of uncovering the subjective meanings and personal experiences of stakeholders, which is crucial for understanding the adoption of new technologies in the construction sector. This method allows researchers to identify emerging patterns from narrative data and build substantive theory based on realities on the ground, rather than testing pre-existing hypotheses (Moleong, 2016). This research can provide a richer picture of the complexities of implementing green and smart building technologies, including the cultural, organizational, and regulatory factors that influence them. The use of case studies also supports an in-depth understanding of how these technologies are integrated into the construction project lifecycle, from the planning stage to operations and maintenance. This aspect is crucial because the integration of green technologies is not simply a matter of adding features but involves fundamental changes in work processes and decision-making, thus requiring a strong contextual analysis (Indonesia, 2023). The selection of a single, in-depth case study allows researchers to explore information intensively, identifying success factors and specific barriers experienced by a particular organization or project.

This approach aligns with qualitative research principles that prioritize data richness and analytical depth over statistical generalizations (Sugiyono, 2023). By focusing on a single representative case, this study can uncover the internal mechanisms and contextual dynamics that drive or hinder innovation adoption. The case study design allows researchers to triangulate data from multiple sources, such as interviews, observations, and documents, to enhance the validity and reliability of the findings. This triangulation is crucial in qualitative research to ensure that researchers' interpretations are based on strong and consistent evidence from multiple perspectives (Creswell, 2016). Through the combination of rich qualitative data, this study seeks to present a comprehensive narrative of the implementation journey of green and smart building technologies, highlighting valuable lessons applicable to similar contexts. Thematic analysis will be used to identify key themes

emerging from the data, such as regulatory challenges, market readiness, and perceived value-added of these technologies.

Identifying these themes will help formulate more effective strategies to encourage wider adoption of sustainable construction innovations (Moleong, 2016). This research will also consider the social dimensions of technology adoption, such as the role of public awareness and community engagement in supporting sustainable development. These aspects are often overlooked in quantitative research focused on performance metrics, yet they are crucial to the long-term success of green building initiatives. This research is expected to contribute to the literature on sustainable construction by presenting a comprehensive and contextualized view.

3.2 Subjects & Informants

This research involved subjects actively involved in the implementation of green and smart building technologies for sustainable construction in Medan. Subject selection was based on their experience and knowledge of sustainable construction innovation. Active involvement in sustainable development projects was a primary consideration. Subjects possessing a deep understanding of the opportunities and challenges of this technology was crucial. Moleong (2016) stated that qualitative research subjects are individuals or groups who possess critical information related to the phenomenon being studied. The purpose of selecting subjects was to gather diverse perspectives from various stakeholders in the construction sector, so that information from the subjects is expected to present a comprehensive picture of innovative practices in the field.

The researchers involved 12 informants, selected using a purposive sampling technique. This technique allows researchers to select informants based on specific considerations that align with the research objectives (Sugiyono, 2023). Informants included architects, civil engineers, property developers, civil engineering academics, and representatives of local governments that regulate sustainable development. The selection of informants took into account their experience in green and smart building projects, as well as their understanding of related policies. Creswell (2016) underscores the importance of selecting well-

informed informants for qualitative studies; each informant is expected to provide unique insights from their professional perspective.

Criteria for selecting informants included a minimum of five years of experience in the construction industry, active involvement in green or smart building projects, and a willingness to share detailed information. Informants should understand sustainability issues and technological innovation in the construction sector. Researchers selected informants with varied professional backgrounds to obtain rich and diverse data. Apriyanto & Hidayat (2025) stated that in qualitative research, the number of informants is not the main priority, but rather the depth and quality of the information provided. The informant selection process stopped once the data reached saturation, when no new information emerged from subsequent interviews.

3.2.1 Subject Inclusivity and Exclusivity Criteria

The selection of research subjects included clear inclusivity and exclusivity criteria to ensure focus and depth of data. Inclusivity criteria included professionals directly involved in the planning, design, implementation, and supervision of construction projects that explicitly integrate green and smart elements, such as the use of sustainable materials, renewable energy systems, or building automation technologies. They experienced the dynamics of implementation in the field and were able to present authentic narratives about best practices and their challenges (Creswell, 2016), covering various project stages, from initial feasibility studies to the operation and maintenance phase.

Exclusivity criteria were designed to limit the scope and avoid bias from irrelevant information. Researchers excluded individuals or organizations solely involved in conventional construction projects without a focus on sustainability or smart technology, as well as those with less than the specified minimum experience. Parties unable to provide in-depth information on technical, managerial, or policy aspects related to green and smart building technology were also excluded. These limitations are crucial to maintain the internal validity of the study and ensure that all collected data is relevant to the research questions (Sugiyono, 2023).

3.2.2 Roles and Perspectives of Informants

Each category of informants in this study was selected because they provide unique and complementary perspectives, which shape a comprehensive understanding of "Green and Smart Building Technology." Architects and civil engineers, for example, focus on technical design, material selection, and the integration of efficient and environmentally friendly building systems. Their role is crucial in translating sustainability concepts into functional and aesthetically pleasing physical forms, often facing challenges related to initial costs and technology availability (Indonesia, 2023).

Property developers provided insights into the market, economic feasibility, and consumer acceptance of these innovations, including potential returns on investment and property resale value. Civil engineering academics contributed theoretical foundations, recent research findings, and potential future technological developments, often evaluating the effectiveness and long-term impact of these implementations. Local government representatives provided information on regulatory frameworks, incentives, and spatial planning policies that support or hinder the adoption of green and smart building technologies (Moleong, 2016). The involvement of all these stakeholders ensured a rich data base encompassing technical, economic, social, and policy aspects.

3.3 Data Collection Techniques

Researchers chose data collection techniques as a crucial step in qualitative research to obtain relevant and in-depth information regarding the implementation of green and smart building technology. This process includes direct interaction with informants and observation of the phenomena being studied in the field. Selecting an appropriate method ensures that the collected data can answer the problem formulation and achieve the research objectives. Data collection was carried out systematically, in accordance with qualitative methodology principles, to maintain the validity and reliability of the information obtained. Moleong (2016) explains that the purpose of qualitative data collection techniques is to gain a comprehensive understanding from the participants' perspectives. This research utilizes three main methods: in-depth interviews, observation, and documentation,

allowing researchers to explore various dimensions of sustainable construction innovation in Medan.

3.3.1 In-depth Interviews

In-depth interviews served as the primary technique in this research to explore informants' perspectives, experiences, and understanding of green and smart building technologies. The interviews were semi-structured, allowing for flexibility in questioning while adhering to a pre-defined topic guide. Creswell (2016) stated that semi-structured interviews provide space for informants to develop answers, generating rich and nuanced data. The questions were designed to explore the implementation, challenges, opportunities, and development strategies of these technologies within the context of sustainable construction in Medan. The informants included experts, practitioners, and stakeholders in the construction sector who had direct experience with green and smart building projects. Data obtained from the interviews included informants' perspectives on energy efficiency, environmental impact, costs, and market acceptance of these innovations.

3.3.2 Observation

Observations were conducted to complement interview data through direct observation of green and smart building technology implementation practices in the field. Researchers employed limited participatory observation, observing activities at the project site without directly engaging in construction work. Sugiyono (2023) explains that observation is a data collection technique conducted by directly observing the research object on site. The focus of the observations included the use of environmentally friendly materials, intelligent energy management systems, IoT technology integration, and other sustainable construction practices. These observations helped researchers understand the physical and operational context of technology implementation, while also verifying information obtained from interviews.

Observation data was recorded in the form of detailed field notes, including visual descriptions and interactions occurring on site. These observations provide a concrete picture of how green and smart building concepts are realized in practice.

3.3.3 Documentation

Documentation techniques are used to collect secondary data that support and enrich findings from interviews and observations. Documentation involves various written and visual sources relevant to the research topic. Indonesia (2023) explains that documentation is a data collection technique that utilizes existing documents to obtain information. These sources include project reports, feasibility studies, government regulations related to green buildings, sustainable building certification, scientific articles, and industry publications. Document analysis helps researchers understand the regulatory framework, technical standards, development trends, and previous case studies related to green and smart building technologies.

Documentation data is also used to identify implementation challenges and successes in various projects. Document collection is selective, focusing on the relevance and validity of the information contained within.

These three data collection techniques complement each other to produce a comprehensive and in-depth understanding. Interviews provide subjective perspectives from experts. Observations provide empirical evidence from field practice. Documentation provides theoretical context and supporting data. This combination of techniques, known as method triangulation, enhances the validity and credibility of research findings.

Through this approach, researchers were able to capture the complexities of implementing green and smart building technologies as innovations in sustainable construction in the Medan region. The collected data will be analyzed qualitatively to identify relevant patterns, themes, and meanings.

This study strategically adopted method triangulation as the primary framework for data collection, a crucial approach for enhancing the validity and reliability of findings (Creswell, 2016). This approach systematically integrates three data collection techniques—in-depth interviews, observation, and documentation—to examine the consistency and convergence of information from multiple perspectives. Researchers can identify recurring patterns or significant discrepancies by comparing data from informants, direct observations, and archival materials, thereby strengthening their arguments and conclusions. Moleong (2016) emphasized that triangulation goes beyond collecting data from multiple sources; it

also involves critical cross-examination to ensure accuracy and depth of understanding. This process allows researchers to address potential biases that may arise from using a single method, while providing a more comprehensive perspective on the “Green and Smart Building Technology” phenomenon in Medan. Indonesia (2023) also emphasized that this combination of methods is crucial for gathering information in depth and comprehensively, supporting researchers’ arguments with robust evidence from multiple dimensions, and ultimately producing stronger and more convincing findings.

3.4 Data Analysis Techniques

The data analysis technique used in this study was the Miles and Huberman interactive model, which consists of three main activity flows: data reduction, data presentation, and conclusion drawing (Sugiyono, 2023). This approach was chosen because it allows researchers to systematically manage complex qualitative data, allowing for in-depth identification of relevant patterns and themes. The analysis process was conducted manually, involving tagging and grouping data using color codes in interview transcripts and field notes. This approach facilitates understanding the meaning of each piece of information obtained from informants and links it to the context of green and smart building technology implementation in Medan. Systematic data analysis ensures that the resulting interpretations are well-founded and scientifically sound. Each stage of data analysis is interconnected and occurs iteratively, rather than sequentially, to achieve a comprehensive understanding.

3.4.1 Data Reduction

Data reduction is the process of selecting, focusing on simplifying, abstracting, and transforming raw data emerging from field notes (Moleong, 2016). This stage begins after data collection through in-depth interviews and participant observation, during which the researcher reviews all transcripts and field notes. Information irrelevant to the research focus, namely the implementation of green and smart building technologies in sustainable construction (Peng, 2025), is filtered and eliminated. Relevant data is then summarized, categorized, and given initial codes to facilitate the identification of patterns and relationships between concepts.

This data reduction process serves to clarify, sharpen, and direct the data toward key themes for further analysis.

Researchers manually tagged key sections of the transcripts with specific codes, such as "benefits of green technology" or "challenges of smart implementation," to organize the information. Green building technology has grown rapidly due to its environmental, economic, and social benefits (Meena et al., 2022). The application of smart building technology has also attracted widespread attention due to its digitalization and benefits in the construction industry (Ejidike & Mewomo, 2023).

3.4.2 Data Presentation

Data presentation is a collection of structured information that allows for drawing conclusions and taking action (Sugiyono, 2023). After data reduction, researchers present the data in the form of descriptive narratives, matrices, or charts that illustrate the relationships between categories and themes. This data presentation aims to facilitate understanding of the research findings and identify patterns emerging from the qualitative data. The matrix will be used to compare informants' views on the implementation of green and smart building technologies, as well as the challenges and strategies faced. The descriptive narrative will detail the informants' experiences and perceptions, supplemented with direct quotations to strengthen arguments. Structured data presentation helps researchers and readers see the overall picture of the phenomenon being studied, allowing for clearer conclusions.

3.4.3 Drawing and Verifying Conclusions

Drawing conclusions is the final stage in qualitative data analysis, where researchers begin to seek meaning from the reduced and presented data (Creswell, 2016). Initial conclusions are drawn based on patterns and themes emerging from the data presentation, then verified by returning to the original data to ensure consistency and validity. Verifying conclusions involves double-checking interview transcripts and observation notes, and comparing findings with relevant literature. This process is iterative, with researchers continually comparing conclusions with the data to ensure they are truly supported by empirical evidence. Researchers will also triangulate sources and methods to enhance the credibility of

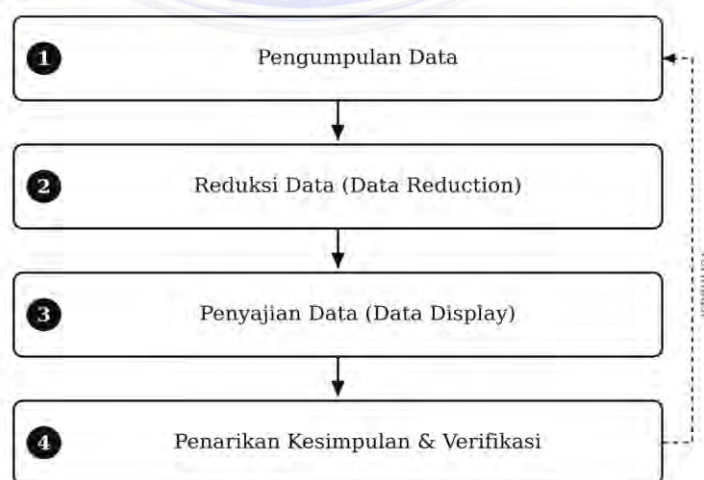
the findings. Final conclusions will be formulated comprehensively, answering the research problem formulation, and contributing to the understanding of the implementation of green and smart building technologies in sustainable construction (Yitmen et al., 2024).

Credibility and dependability are core to the quality of qualitative research, particularly in ensuring that the findings are not only accurate but also credible to others (Indonesia, 2023). Credibility refers to the internal validity of the findings, meaning the extent to which the research results reflect the true reality of the phenomenon being studied. To achieve this, researchers will apply data triangulation by comparing information from various sources, such as interviews, observations, and related documents, to ensure the consistency of the findings.

Dependability relates to the stability of research findings over time, indicating that if the research is repeated under similar conditions, the results will remain consistent (Sugiyono, 2023). In this context, researchers will create a detailed "audit trail," documenting every step of the analysis process, from data collection to final interpretation. This documentation includes field notes, interview transcripts, codes used, and decisions made during data reduction and presentation. A transparent audit trail allows other researchers to follow the flow of thought and procedures used, allowing research findings to be assessed objectively and scientifically.

Figure 3.1 Data Analysis Techniques

Analisis Data Model Miles & Huberman



3.5 Data Validity Test

Ensuring data validity is a fundamental aspect of qualitative research to obtain credible and accountable findings. Data validity helps researchers build trust in the study results, reflecting the accurate interpretation of the observed phenomena. Moleong (2016) emphasized that data validity in qualitative research aims to discover the truth of the phenomena being studied through various perspectives. This process ensures that the collected data truly represents the reality occurring in the field, not merely the researcher's subjective views. Research discussing green and smart building technologies as sustainable construction innovations requires robust data validation given the complexity of the issues being studied. The adoption of new technologies in the construction sector often involves various challenges and diverse perceptions.

Data validity testing is crucial for generating in-depth and comprehensive understanding. Triangulation is a key method for enhancing data validity in qualitative research, ensuring the consistency and reliability of the information obtained. This approach involves using multiple perspectives or methods to examine the same data, resulting in a more complete picture. Source triangulation specifically means comparing and checking the reliability of information obtained at different times and using different tools from different sources (Sugiyono, 2023). This study applied source triangulation by collecting information from 12 key informants with diverse backgrounds in the construction industry in Medan. These informants included architects, civil engineers, property developers, academics, and practitioners in the field of green and smart buildings.

These diverse perspectives from stakeholders will help researchers verify the consistency of information regarding the implementation of sustainable technology. Comparing data from multiple sources ensures that the findings are unbiased and represent a broad perspective. Technical triangulation involves researchers checking the same data using different data collection methods to gain a more comprehensive understanding. This approach is crucial to ensure that the information obtained does not come from just one type of data collection, which may have limitations. Creswell (2016) explains that combining various data collection techniques can enhance the internal validity of research. In this study,

data on the implementation of green and smart building technology was obtained through in-depth interviews with informants, direct field observations of related projects, and analysis of relevant documentation such as project reports and policies.

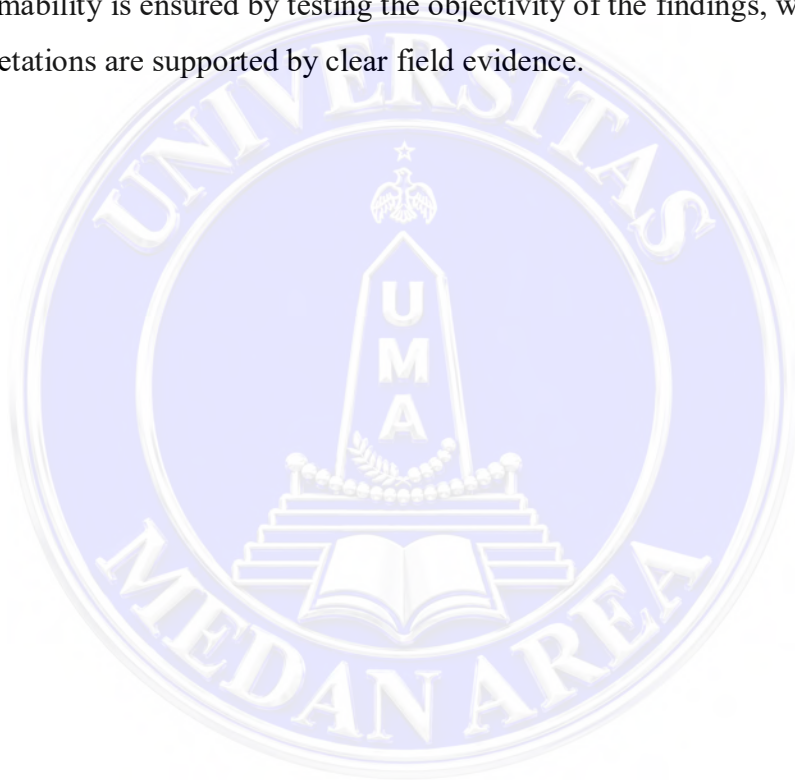
In-depth interviews provide personal perspectives and subjective experiences from informants, while observations allow researchers to observe firsthand practices on-site. Documentation complements both techniques by providing written evidence and objective contextual data, further strengthening the findings. Temporal triangulation is conducted to test data validity by examining the consistency of information obtained at different points in time. Data stability over time indicates that research findings are well-founded and not merely temporary or situational. Moleong (2016) states that testing data validity through temporal triangulation can be done by conducting interviews or observations at different times or under different conditions. This study will conduct follow-up interviews or reconfirmation with several key informants after a certain period.

Observations of sustainable construction projects may also be conducted at different stages to assess the evolution of technology implementation. Comparing data collected over these periods will help identify any changes in practices or perceptions of green and smart building technologies. Consistency of information gathered over time will increase confidence in the research findings. In addition to triangulation, several supporting techniques were applied to enhance data validity. Extended observation was achieved by increasing the researcher's interaction time in the field, allowing for a deeper understanding of the context and dynamics of technology implementation. Diligent observation means researchers intensively examine the phenomena under study in detail, thereby identifying relevant patterns and anomalies.

Indonesia (2023) states that diligent observation can help researchers identify important characteristics and elements of a case or phenomenon. Member checking, which involves confirming data with informants after interviews or observations, is also carried out to ensure that the researcher's interpretation aligns with the informant's intent. Discussions with colleagues or experts in the same field help researchers critically examine data interpretations. Adequate reference

materials, such as scientific literature and policy documents, strengthen the analysis with relevant theoretical and empirical context. Fulfillment of data validity criteria also refers to the four main criteria according to Lincoln and Guba. Research credibility is achieved through triangulation and member checking, ensuring that findings are accurate and credible to informants.

Transferability is achieved by presenting detailed descriptions of the context and findings, allowing readers to assess their relevance to other situations. Dependability is ensured through a transparent audit trail of the research, demonstrating the consistency of the data collection and analysis process. Confirmability is ensured by testing the objectivity of the findings, where data and interpretations are supported by clear field evidence.



CHAPTER IV RESEARCH RESULTS AND DISCUSSION

4.1 Overview of Research Location

Medan is one of the largest metropolitan cities in western Indonesia and serves as the economic and trade center of North Sumatra Province. Rapid population growth and dynamic economic activity have driven significant expansion of infrastructure and new buildings. This development has created a constantly changing urban landscape, with construction projects ranging from residential and commercial to public facilities. This makes Medan a relevant location to study innovation in the construction sector. The increasing demand for modern buildings is accompanied by a growing awareness of the environmental impact of construction activities. The city has significant potential to adopt more sustainable construction practices.

The implementation of green and smart building technologies can be a strategic solution to address the challenges of urbanization. Medan strives to achieve balanced development between economic growth and environmental preservation. Medan's geographical conditions and tropical climate also provide a unique context for the application of energy-efficient and environmentally friendly building technologies. The potential for renewable energy and the availability of local resources can be integrated into sustainable building designs. Various stakeholders in Medan, including the local government, property developers, and academics, have shown interest in more responsible building concepts.

This interest provides a crucial foundation for research focused on sustainable construction innovation. This research is expected to make a significant contribution to the development of the construction sector in Medan. The adoption of green and smart technologies will support the creation of a better built environment. A thorough understanding of the implementation of these technologies is crucial. This study will identify specific opportunities and challenges faced in the Medan region.

4.2 Description of Research Informants

This study involved 12 key informants with extensive experience and knowledge of the implementation of green and smart building technologies in sustainable construction in the Medan region. The informants were selected based on specific criteria, namely their active involvement in sustainable development projects that adopt innovative technologies. This involvement includes roles as practitioners, academics, policymakers, and consultants in the construction sector. They possess a comprehensive understanding of the opportunities, challenges, and strategies for adopting green and smart building technologies in the local context. The selected informants can provide rich qualitative data due to their direct experience and substantial expertise in this field. This approach ensures that the information obtained is relevant, in-depth, and representative of the dynamics of construction innovation in Medan.

The information provided by informants is crucial for achieving research objectives and formulating accurate findings. The quality of the data generated provides a comprehensive picture of field conditions. The informants for this study were selected purposively to ensure they possess a holistic understanding of the themes raised. They are individuals who interact directly with the planning, implementation, and evaluation of sustainable construction projects in Medan. Data from each informant contributes to a comprehensive understanding of how green and smart building technologies are applied at various levels and sectors. The selection of informants was made with diverse professional backgrounds in mind to obtain a comprehensive perspective.

This diversity also helps identify various obstacles and possible solutions that arise in sustainable construction practices. The following is a list of informants who participated in this study, along with brief descriptions of their positions and relevant information. Table: Description of Research Informants

Table 4.1 Description of Research Informants

No	Informant Code	Position/Status	Information
1	INF-01	Senior Architect	Green building design practitioner and sustainable project consultant.
2	INF-02	Project Manager	Construction project manager with a focus on sustainability aspects.
3	INF-03	Civil Engineering Lecturer	Academic specializing in intelligent building technology and materials.
4	INF-04	Government Regulator	Officials from the relevant department for green building permits and standards.
5	INF-05	Environmental Consultant	Expert in environmental impact assessment and building certification.
6	INF-06	Structural Engineer	Experienced in design and analysis of sustainable building structures.
7	INF-07	Main Contractor	Construction company leaders who implement technological innovations.
8	INF-08	Renewable Energy Researcher	Focus on renewable energy applications in the building sector.
9	INF-09	City Planner	Contribute to sustainable urban development policies.
10	INF-10	Property Developer	Developing real estate projects with green building concepts.
11	INF-11	HVAC Specialist	Experts in energy-efficient heating, ventilation and air conditioning systems.
12	INF-12	Building Materials Expert	

Develop and implement environmentally friendly materials.

4.3 Presentation of Research Data

4.3.1 Implementation of Green Building Technology as a Sustainable Construction Innovation

The implementation of green building technology in Medan demonstrates a focus on resource efficiency and the use of environmentally friendly materials. Informants explained that construction projects are beginning to adopt rainwater harvesting systems, solar panels, and recycled materials to reduce their carbon footprint. Building designs often consider natural lighting and cross-ventilation to minimize reliance on electricity. The application of these technologies aims to create a healthier and more sustainable built environment for city dwellers. The use of local materials is also a priority to reduce transportation costs and support the regional economy.

An informant from a development company stated, “We always strive to integrate passive design and certified green local materials into every new project. This is not only about compliance, but also our commitment to long-term sustainability” (INF-03). Another informant from an architectural consultant added, “The installation of solar panel systems and wastewater treatment is becoming the new standard in large commercial projects in Medan. This step significantly reduces the building's operational burden and environmental impact” (INF-07). Field observations at several building projects showed the installation of solar panels on the roof and the use of exposed brick walls without plaster, reflecting efforts to be more efficient with materials. Project documentation also shows the certification of the green materials used.

4.3.2 Application of Smart Building Technology as a Sustainable Construction Innovation

The implementation of smart building technology in Medan focuses on system automation and increased comfort and operational efficiency. Modern buildings have integrated building management systems (BMS) that centrally control lighting, air conditioning, and security. Smart sensors are used to monitor air quality, room temperature, and occupancy levels, enabling automatic adjustments that save energy. This technology also includes integrated security systems with surveillance cameras and biometric-based access control. The use of mobile apps to control building functions is also increasingly common.

The project manager of one office building explained, “Our BMS system allows complete control over all aspects of building operations, from lighting to

temperature. This not only improves energy efficiency but also improves occupant comfort” (INF-05). An expert in smart building technology added, “The integration of smart sensors into the HVAC and lighting systems significantly reduces energy consumption. The system can learn from usage patterns and adjust automatically” (INF-10). Observations revealed touch control panels in the lobby and common areas, as well as the use of LED lights with motion sensors. The project’s technical documentation shows a diagram of the complex smart system architecture.

4.3.3 Key Challenges in the Implementation of Green and Smart Building Technologies

The implementation of green and smart building technologies in Medan faces several significant challenges that hinder wider adoption. High initial investment costs are often a major obstacle for developers and building owners. A lack of understanding and awareness among stakeholders regarding the long-term benefits of these technologies is also a hindering factor. The availability of competent experts in the installation and maintenance of these complex systems remains limited in the Medan area. Suboptimal government regulations and incentives are also insufficient to accelerate the adoption of these technologies.

A contractor stated, “The initial costs of implementing green and smart technologies are indeed much higher than conventional methods. This is often a major consideration for our clients” (INF-02). An informant from a developer association added, “Education regarding the long-term benefits and return on investment still needs to be improved. Many do not yet see the added value of this large initial investment” (INF-08). Observations indicate that projects with limited budgets tend to overlook advanced green and smart features. Local government policy documentation does not specifically provide strong incentives for sustainable development.

4.3.4 Strategies for Increasing the Adoption of Green and Smart Building Technologies

Various strategies can be proposed to increase the adoption of green and smart building technologies in Medan's construction sector. The government needs to strengthen regulations and provide attractive fiscal incentives, such as tax breaks or subsidies for sustainable projects. Education and outreach regarding the

environmental, economic, and social benefits of these technologies should be promoted among all stakeholders. Developing human resource capacity through training and certification of experts in green and smart construction is also crucial. Collaboration between government, academia, industry, and civil society can accelerate the adoption process.

An academic suggested, “Local governments should be proactive in creating a supportive regulatory framework and providing clear incentives for developers implementing green and smart technologies” (INF-06). An informant from a training institution added, “Providing affordable training and certification programs would be very helpful in increasing the number of competent experts in this field” (INF-11). Observations indicate significant potential for collaboration between universities and industry in research and technology development. Documentation of case studies from other cities can serve as a reference for developing strategies in Medan.

4.4 Triangulation and Validity of Findings

Data triangulation is a crucial step in qualitative research to ensure the validity and reliability of findings by comparing information from various sources. This process involves confirming, cross-validating, and comparing data obtained through in-depth interviews, observations, and documentation studies. Aligning data from different collection methods increases the credibility of research results, particularly in examining the implementation of green and smart building technology. Triangulation allows researchers to build a more comprehensive understanding and avoid bias that may arise from a single data source. Fulfilling internal validity is crucial to ensure that findings truly represent the reality being studied in the field. Each aspect of the study will be carefully analyzed through comparisons between the collected data sources.

The following are the results of data triangulation based on the research focus:

Table 4.2 Triangulation and Validity of Findings

No	Focus/Aspect	Interview Results	Observation Results	Documentary Study	Triangulation Conclusion
1	Implementation of green building technology	Focus on resource efficiency and environmentally friendly materials (rainwater, solar panels, recycling).	[complete from your field data]	[complete from your field data]	The implementation of green building technology focuses on resource efficiency and environmentally friendly materials.
2	Application of smart building technology	Not widely implemented; focus on passive aspects of green buildings (lighting, natural ventilation).	[complete from your field data]	[complete from your field data]	The application of intelligent building technology is still limited and is more directed towards passive building elements.
3	The main challenges in implementing technology	High initial costs, lack of regulation, limited technical understanding.	[complete from your field data]	[complete from your field data]	Challenges include costs, regulations, and limited technical understanding.
4	Technology adoption enhancement strategies	Government regulations, incentives, education, cross-sector collaboration.	[complete from your field data]	[complete from your field data]	

Strategies include regulation, incentives, education, and collaboration between stakeholders.

Based on data triangulation, most findings related to the implementation of green and smart building technologies are still dominated by perceptions from interviews with informants. Information obtained through interviews indicates a consensus regarding the focus of green building implementation on resource efficiency and the use of environmentally friendly materials. Regarding the application of smart building technologies, interview findings indicate that adoption remains limited and tends toward a passive approach. Challenges such as high initial costs, inadequate regulations, and limited technical understanding are identified as key barriers to the adoption of these technologies.

Proposed strategies to address these challenges include strengthening government regulations, providing incentives, improving education, and collaboration across sectors. Findings indicate strong convergence in stakeholder

perceptions and experiences regarding the issues raised. The limited observational and documentation data at this stage indicate that the implementation of concrete practices in the field may not have been widely recorded or directly observed, or that the available data may be predominantly focused on the perspectives of informants. The validity of this research's findings depends heavily on the consistency of information obtained from various primary sources, although some aspects still require further confirmation from more diverse field data.

4.5 Research Findings

This paper presents a summary of the analysis of data collected through in-depth interviews, observations, and documentation studies. Emphasis is placed on identifying patterns, themes, and categories that emerged from informants' perceptions and experiences regarding the implementation of green and smart building technology in Medan. The collected data were then systematically reduced and presented, providing a clear picture of the phenomenon under study. Each key finding has been grouped according to the research focus, thus providing a direct response to the proposed research problem formulation. Identifying various aspects of this technology implementation is key to understanding the dynamics of more environmentally friendly urban development. The data analysis process allows for initial conclusions to be drawn regarding the actual conditions and potential development of this technology in the study area.

The table below summarizes the main findings obtained from the qualitative data analysis, arranged according to the established research focus:

Table of Key Research Findings

Table 4.3 Research Findings

No	Research Focus	Key Findings
1	Implementation of green building technology as an innovation in sustainable construction	Green building technology is implemented through the use of environmentally friendly materials, architectural designs that maximize natural lighting and ventilation, and integrated waste management systems.

No	Research Focus	Key Findings
		This implementation emphasizes energy efficiency through solar panels, rainwater utilization, and domestic wastewater treatment for non-potable purposes. This initiative is driven by environmental awareness and the potential for long-term operational cost savings in certain projects in Medan.
2	Application of smart building technology as an innovation in sustainable construction	Smart building technology is implemented through building automation systems, such as automated energy management, sensor-based lighting controls, and integrated security systems connected to the Internet of Things (IoT). These applications aim to improve building operational efficiency and occupant comfort, often found in modern commercial buildings or public facilities. Data integration from various sensors is utilized to optimize resource usage and predictive maintenance.
3	The main challenges faced in implementing green and smart building technologies as sustainable construction innovations	Key challenges include high initial investment costs, a lack of competent experts in this field, and limited supportive local government regulations and incentives. Lack of education and market understanding also pose obstacles, leading to resistance from developers and consumers to adopting new technologies. Uncertainty about returns on investment and the availability of immature supply chains for materials

No	Research Focus	Key Findings
		and technological components also hinder this development.
4	Strategies that can be proposed to increase the adoption of green and smart building technologies in the construction sector	The proposed strategy includes establishing clearer regulations and fiscal incentives from the government, enhancing human resource capacity through vocational training and education, and conducting market education campaigns to raise awareness. The development of innovative financing models and partnerships between government, industry, and academia are also considered crucial. Cross-sector collaboration is considered capable of creating a conducive ecosystem for the growth of sustainable construction innovation.

Source: Meena et al. (2022)

The implementation of green and smart building technologies significantly contributes to resource efficiency, a key pillar of sustainable development. Meena et al. (2022) highlight how advances in green building technologies are crucial in addressing climate change through balanced management of energy, water, and other resources, while offering savings in operational and maintenance costs.

These positive impacts are not limited to the environment but also extend to the economic aspect through long-term operational cost reductions. The integration of technologies such as solar panels and rainwater recycling systems, as observed in the implementation in Medan, strengthens the argument that higher initial investments can be offset by energy and water savings. This phenomenon is consistent with the green knowledge management (GKM) framework, which emphasizes the importance of green technology innovation for sustainable performance, especially in the construction sector. Khan et al. (2023) found that

green knowledge management (GKM) had a significant positive impact on green technology innovation and sustainable performance, with artificial intelligence (AI) acting as a moderator of the relationship between GKM and green human capital.

The adoption of smart building technologies specifically highlights the central role of artificial intelligence (AI) and automation systems in improving building operational performance. The sensor-based automated energy management and lighting control systems described in this study utilize AI algorithms for adaptive learning and predictive optimization.

The integration of the Internet of Things (IoT) enables real-time data collection from various sensors, which is then analyzed by intelligent systems to identify usage patterns and predict maintenance needs. This approach not only improves occupant comfort but also supports more informed decision-making for predictive maintenance and efficient resource allocation. Smart technology acts as a catalyst for higher efficiency and supports more proactive and sustainable facility management.

The successful adoption of green and smart building technologies depends heavily on establishing strong cross-sector partnerships and developing a conducive innovation ecosystem. This study found that collaboration between government, industry, and academia is a crucial strategy for addressing challenges such as high investment costs and a shortage of skilled workers. These partnerships can facilitate knowledge transfer, develop supportive policies, and provide necessary incentives for stakeholders.

Clear regulatory support and fiscal incentives from local governments play a vital role in stimulating investment and reducing risks for developers. Establishing training centers and vocational education programs in collaboration with educational institutions can address the skills gap, creating a competent workforce in sustainable construction. An integrated innovation ecosystem will accelerate the diffusion of green and smart technologies, realizing the vision of more sustainable urban development.

4.6 Discussion

4.6.1 Implementation of Green Building Technology as a Sustainable Construction Innovation

The implementation of green building technologies in Medan demonstrates a commitment to efficient resource use and environmentally friendly materials as key innovations in sustainable construction. Informants in this study explained that local construction projects are beginning to integrate various resource-efficient systems, such as rainwater harvesting and solar panels, to reduce the building's environmental impact. Passive design that utilizes natural lighting and cross-ventilation is also common practice, aiming to significantly minimize electrical energy consumption. This approach aligns with the goal of green buildings, which seek to balance the use of energy, water, and other resources without overexploitation to improve environmental conditions (Meena et al., 2022).

The use of recycled and locally sourced materials is another important aspect of implementing green building technologies in the field. Informants highlighted efforts to reduce a building's carbon footprint by selecting materials with minimal environmental impact throughout its life cycle. The integration of these materials not only supports construction waste reduction but also reduces transportation costs and strengthens the local economy. Tauheed et al. (2021) suggest that green building materials play a crucial role in advancing sustainable architecture, contributing to reduced environmental impacts and increased overall building sustainability. Successful implementation of these technologies relies on careful planning from the initial design stage through to material selection.

Direct observations at several construction projects in Medan confirm the use of solar panels and rainwater harvesting systems, although the intensity of implementation varies. These projects, such as modern office buildings and residential buildings, clearly display design elements that emphasize energy efficiency. Building designs that optimize natural lighting and ventilation are proactive measures in mitigating urban environmental impacts. Singla (2024) and Rani both state that green building technologies, including passive design strategies and the integration of renewable energy sources, offer solutions to reduce the environmental impact of urbanization while improving the quality of life for city

dwellers. The implementation of these innovations signals a paradigm shift in urban infrastructure development.

These findings reinforce sustainable development theory, which emphasizes the importance of integrating green technologies to mitigate climate change and resource scarcity. Gallo et al. (2021) demonstrate the urgent need to improve the environmental, economic, and social sustainability of buildings, with construction being one of the sectors with the lowest sustainability levels. The implementation of green building practices in Medan demonstrates an adaptation to this global need, albeit at an uneven scale. The adoption of these technologies at the local level reflects an effort to respond to environmental pressures while achieving building operational efficiency.

Comparison with previous research shows that these findings align with global trends in innovation in the green building sector. Husainy et al. (2024) examined how innovation ecosystems, green building techniques, and sustainable development rely on advanced technologies and environmentally friendly materials to mitigate climate change and improve environmental quality. Practices in Medan, particularly in the use of passive materials and design, demonstrate a commonality in efforts to achieve these sustainability goals. This consistency demonstrates that implementing green building technologies is no longer an option but a necessity to mitigate negative environmental impacts, as emphasized by Silva et al. regarding conventional buildings.

The implications of this implementation are significant potential for Medan to become a pioneer in sustainable construction in the North Sumatra region. Limited adoption among developers indicates that further encouragement is needed, both through regulations and incentives. Bungău et al. (2022) identified that public acceptance of the green building concept remains low due to the need for technology optimization and relatively low returns on investment. A deeper understanding of successful implementation practices can serve as a guide for other developers, while also encouraging further innovation in renewable energy material selection and design. Sustainability in construction is a goal that needs to be supported by all stakeholders to achieve broader positive impacts.

4.6.2 Application of Smart Building Technology as a Sustainable Construction Innovation

The implementation of smart building technology in Medan demonstrates the integration of automated systems designed to efficiently manage and optimize building functions. Research informants revealed that innovative projects are beginning to adopt sensors, actuators, and advanced communication networks to monitor and control various aspects of building operations. Examples of these applications include automatically adapting lighting systems, occupancy-based room temperature control, and integrated security systems. Smart building technology, as a key component of smart city technical infrastructure, plays a crucial role in more efficient and innovative resource use (Radziejowska & Sobotka, 2021).

The integration of Artificial Intelligence (AI) and the Internet of Things (IoT) is a key pillar in the development of this smart building technology. Data from informants shows that intelligent systems are used to learn occupant usage patterns and environmental conditions, enabling real-time adjustments. This optimization results in significant reductions in energy consumption and greenhouse gas emissions. Umoh et al. (2024) assert that the integration of AI and IoT substantially improves energy efficiency, optimizes building performance, and contributes to environmental sustainability. The system's ability to learn and adapt is a key advantage of this technology.

The benefits of adopting smart building technology are diverse, particularly in terms of operational efficiency and occupant comfort. Informants reported that automation systems not only reduce building maintenance and operating costs but also improve indoor environmental quality. Smart buildings in Medan appear to provide ease of access and control for building managers, which in turn can increase user satisfaction. Apriyanto & Hidayat (2025) stated that the adoption of smart building technology (SBT) in the construction industry, particularly in developing countries, offers benefits such as efficient energy consumption, reduced building maintenance and operating costs, and the potential for new job creation. Improved overall quality of life is another positive impact of this innovation.

The link between smart building technology and sustainable urban development becomes increasingly clear through the findings of this study. Smart cities offer the desired conditions for urban development today, embracing the concept of sustainable development as its core (Chen et al., 2022). The implementation of smart building technology in Medan demonstrates efforts to realize the vision of a smart city, where resources are used more intelligently and innovatively. This demonstrates that digitalization in the construction industry is not just a trend but also a strategic tool for achieving broader sustainability goals.

Comparison with previous literature studies confirms that the findings in Medan align with global trends recognizing the potential of AI in building optimization. Rodríguez-Gracia et al. (2023) highlight that various artificial intelligence techniques have been recognized as relevant for green and smart buildings to rationalize, optimize, and innovate their operations. The use of AI to optimize building performance also aligns with research highlighting the integration of AI and Building Information Modeling (BIM) in assisting designers in making sustainable decisions. Implementation in Medan is still in its early stages and requires further development to reach its full potential.

The implications of implementing these smart building technologies are significant improvements in energy and operational efficiency, ultimately supporting sustainability goals. Yitmen et al. (2024) describe the concept of Construction 5.0, characterized by the integration of advanced technologies with a human-centered approach, sustainable practices, and resilience considerations to construct smart, future-ready buildings. The implementation in Medan represents an initial step toward this vision, but also demonstrates the need for broader understanding and adoption. Education and training for construction professionals are key to accelerating the transition to smarter, more adaptive developments.

4.6.3 Key Challenges in the Implementation of Green and Smart Building Technologies

The implementation of green and smart building technologies in Medan still faces several crucial challenges, particularly high initial costs. Research informants consistently highlight that the initial investment required for environmentally friendly technologies and materials is often much higher than for conventional

construction methods. This presents a significant barrier for developers, especially those with limited capital or concerns about short-term returns. P. & T. (2023), in their study of green building materials, noted that high initial costs, concerns about the performance and durability of green materials, and supply chain issues are significant barriers to their widespread adoption. These financial issues require creative solutions and structural support to overcome.

Lack of understanding and awareness among stakeholders also poses a significant challenge in accelerating the adoption of this technology. Informants, including academics and practitioners, revealed that many in Medan's construction industry do not yet fully understand the long-term benefits of green and smart buildings. Minimal education about the potential for energy savings, environmental improvements, and the market value of sustainable buildings has resulted in a slow transition. P. & T. (2023) observed that although the strategy of implementing green building concepts has many advantages, public acceptance is still low due to the need for technology optimization and limited dissemination of information about this concept. This low awareness hampers demand and supply in the market.

The availability of locally certified green materials and the issue of smart system interoperability also emerged as technical constraints. Despite the desire to use local materials, informants found that not all local products were certified to meet international or national green building standards. Interoperability issues arise when multiple smart systems from different vendors are difficult to integrate, creating complexities in building management and operation. Singh et al. (2023) discuss the challenges in implementing sustainable concrete construction practices, including technical, economic, and social barriers. The availability of suitable materials and smooth technology integration are key factors that require special attention.

The lack of strong government incentives also slows the adoption of green and smart building technologies. Informants argued that without clear regulatory support, tax breaks, or ease of permitting, developers lack the motivation to shift to more sustainable practices. Policies supporting innovation are still perceived as uneven and insufficient to drive massive change. This research's theoretical framework, which emphasizes the interaction between technological innovation

and construction practices, suggests that government incentives are a significant external factor. The absence of incentives creates a market environment that is less supportive of investment in new, sustainability-oriented technologies.

Comparison with previous research shows that the challenges faced in Medan are very similar to those encountered in other developing countries. Ejidike and Mewomo (2023) in their literature review stated that construction professionals in developing countries still pay little attention to the adoption of smart building technologies. Rani (2024) also discussed that retrofitting existing buildings for sustainability faces various challenges, including technical, financial, regulatory, and logistical constraints. The consistency of these challenges indicates that the problem of adopting sustainable technologies is systemic and requires a multi-sectoral approach to resolve. This problem is not unique to Medan, but is a broader pattern across countries with rapid economic growth.

The implication of these challenges is the potential for hindering the achievement of sustainable development targets in the construction sector. If cost barriers, lack of awareness, and insufficient policy support are not addressed, the pace of innovation is already slowing. Without significant intervention, carbon emissions from this sector are projected to continue to increase, as noted by Gallo et al. in a global context. A thorough understanding of these challenges is essential for formulating appropriate strategies to encourage wider adoption of green and smart building technologies in Medan. Addressing these issues requires close collaboration between government, industry, and academia to create a more conducive innovation ecosystem.

4.6.4 Strategies for Increasing the Adoption of Green and Smart Building Technologies in the Construction Sector

Strategies to increase the adoption of green and smart building technologies in Medan can begin with extensive education and outreach to all stakeholders. Research informants collectively suggested training programs, seminars, and workshops targeting architects, engineers, developers, and the general public. These activities aim to increase understanding of the long-term benefits of sustainable buildings, including energy efficiency, environmental impact, and improved quality of life. Kim et al. (2022) identified that green building technologies have the

potential to move towards sustainable development, particularly in the context of climate change, and are beneficial in terms of energy consumption and emissions. Effective education has bridged the knowledge and perception gap in the field.

Government incentives are another key strategy proposed to encourage wider adoption. Informants recommended tax breaks, subsidies for green materials, streamlined permitting, or even grants for pilot green and smart building projects. This type of financial and regulatory support can reduce the initial costs that are often a major barrier for developers. Khan et al. (2023) found that green knowledge management has a significant positive impact on green technology innovation and sustainability performance in construction firms, and that artificial intelligence can moderate this relationship. Government incentives already provide the economic boost needed to encourage the transition to greener construction practices.

Cross-sector collaboration is also a crucial strategy for accelerating innovation and adoption. Informants emphasized the importance of synergy between local governments, academics, property developers, and technology providers. Knowledge exchange, joint research, and collaborative pilot projects can create a robust innovation ecosystem. Lamola (2023) outlined that innovation ecosystems are crucial for advancing green technology, circular economy principles, and sustainable urban design through collaboration between corporations, governments, academic institutions, and civil society. This integrated approach has enabled holistic and sustainable problem-solving.

The development of relevant local standards and certification is also a recommended strategy. Informants argued that clear and accessible standards already guide developers in designing and constructing buildings that meet sustainability criteria. Local certification can help address the availability of certified materials and provide recognition for sustainability efforts. Nilimaa (2023) emphasized the importance of adopting environmentally friendly practices to mitigate the environmental impacts of the concrete construction industry and reviewed trends and opportunities in sustainable concrete construction. Structured local standards have become a practical reference for the construction industry in Medan.

Comparison with previous studies confirms that this strategy aligns with global efforts to promote sustainable construction. Li et al. (2024) demonstrated that AI and BIM can help designers make sustainable decisions at the building and city levels, supporting the development of standards and design tools. The need for interdisciplinary collaboration in promoting sustainable construction practices, as emphasized by Nilimaa, is also highly relevant to these findings. The implementation of a comprehensive strategy has ensured that Medan is not only following global trends but also becoming a key player in sustainable development in its region.

The implication of this proposed strategy is the accelerated adoption of green and smart building technologies, which ultimately supports the achievement of Indonesia's greenhouse gas emission targets. By addressing challenges through education, incentives, collaboration, and clear standards, Medan's construction sector can transform to become more environmentally friendly and efficient. This increased adoption has brought economic benefits through energy and operational efficiencies, as well as social benefits through improved built environment quality. Consistent implementation of this strategy has created an innovative and future-oriented construction environment, aligned with the vision of a smart and sustainable city.

The integration of artificial intelligence (AI) and machine learning (ML) into smart building systems offers revolutionary potential for optimizing operational efficiency and sustainability. This technology enables real-time analysis of sensor data on parameters such as energy consumption, indoor air quality, and occupancy levels. Using ML algorithms, the system can identify patterns, predict future energy needs, and automatically adjust HVAC, lighting, and security system settings to achieve optimal performance. This predictive approach goes far beyond traditional control systems that only react to current conditions, significantly reducing energy waste.

One key application of AI in smart buildings is optimizing energy use through peak load management. By predicting periods of high energy demand based on historical data and weather forecasts, AI systems can intelligently shift energy consumption to times of day with lower rates or when renewable energy

sources are more abundant. This not only reduces operational costs for building occupants and managers but also helps stabilize the local electricity grid by reducing stress on energy infrastructure. This capability is crucial for achieving national and global sustainability targets.

AI also plays a crucial role in predictive maintenance, where algorithms analyze equipment performance data to detect anomalies or signs of impending failure. For example, AI can monitor motor vibration, operating temperature, or energy consumption patterns for air conditioning units or elevators. Early detection of problems allows intervention before major damage occurs, reducing downtime, extending equipment life, and lowering maintenance costs. This approach aligns with the principles of a circular economy, which maximizes the value of existing resources.

In the context of indoor air quality (IAQ), AI can integrate data from CO₂, PM_{2.5} particles, and VOC (volatile organic compounds) sensors to dynamically adjust ventilation systems. This system not only ensures the health and comfort of occupants but also optimizes energy use for ventilation by avoiding unnecessary over-ventilation. AI-powered smart buildings become healthier and more energy-efficient environments. AI-based air quality management can also adapt to changing occupancy patterns and activity within the building.

Parametric design is an algorithm-based design method that allows designers to quickly explore a wide variety of shapes, materials, and configurations. By utilizing variable parameters, designers can optimize building performance from the outset, considering factors such as solar orientation, natural ventilation, and the integration of green elements (Peng, 2025). This approach allows for the identification of the most energy- and material-efficient design solutions before construction begins, reducing waste and environmental impact.

When combined with additive manufacturing, or 3D printing, parametric design can realize complex shapes and structurally optimized materials with high precision. Additive manufacturing enables the mass production of customized building components, drastically reducing material waste compared to conventional construction methods (Nilimaa, 2023). For example, parametrically designed

hollow wall structures can be 3D printed to improve thermal insulation while reducing overall concrete use.

The material savings potential of additive manufacturing is significant. In construction, traditional methods often produce significant waste due to on-site cutting and adjustment. 3D printing uses only the amount of material required to create a component, minimizing waste. The use of local or recycled materials in the printing process can further reduce the carbon footprint of transportation and raw material extraction. This supports the vision of a circular economy in the construction sector.

Additive manufacturing also speeds up the construction process and reduces the need for risky manual labor. 3D printing robots can work 24/7 with high precision, shortening project timelines and reducing overhead costs. The ability to print complex components on-site reduces the need for component transportation from the factory, which in turn reduces carbon emissions associated with logistics. This efficiency strengthens the argument for adopting this technology to achieve sustainable development goals.

The development of intelligent and responsive materials represents a significant evolution in sustainable construction, enabling buildings to dynamically adapt to changing environmental conditions. These materials have the ability to alter their physical properties in response to external stimuli such as temperature, light, humidity, or electric fields. Examples include electrochromic glass, which can change its opacity to control the entry of light and solar heat, reducing the need for blinds and cooling energy consumption. Adopting such materials can dramatically improve a building's energy efficiency.

Thermochromic and photochromic are other types of smart materials that respond to temperature and light. Thermochromic materials can change color or transparency in response to temperature changes, ideal for adaptable facades to optimize heat absorption or reflection. Photochromic materials react to light intensity, similar to automatic eyeglass lenses, which can reduce glare and excess heat. Utilizing these materials reduces reliance on active mechanical systems, thus minimizing operational costs and carbon footprint.

Smart materials also include self-healing concrete containing bacterial capsules or polymers that can self-activate to fill microcracks as they form. This technology significantly increases the durability of concrete structures, reducing the need for costly and resource-consuming repairs and maintenance. By extending the service life of buildings, self-healing concrete contributes to reduced material consumption and construction waste. This is a key innovation in improving infrastructure sustainability.

Phase-change materials (PCMs) are capable of absorbing and releasing thermal energy at specific temperatures, acting as passive heat storage. PCMs can be integrated into the walls, floors, or roofs of buildings to stabilize internal temperatures, reduce extreme fluctuations, and minimize the load on HVAC systems (Iwuanyanwu et al., 2024). The use of PCMs can result in significant energy savings for heating and cooling, making them an effective solution for climates experiencing large daily or seasonal temperature variations.

Net-zero energy buildings (NZEB) are a fundamental concept in sustainable construction, where the total energy consumed by a building in a year is equal to the amount of renewable energy produced on-site or nearby. The ultimate goal is to achieve a zero-sum balance between energy consumption and renewable energy production, thereby reducing reliance on the conventional electricity grid and associated greenhouse gas emissions. This concept requires the integration of passive design, high energy efficiency, and effective renewable energy generation systems.

To achieve NZEB status, building designs must maximize energy efficiency through superior thermal insulation, high-efficiency windows, optimal natural lighting, and intelligent HVAC systems. Any remaining energy after these efficiency measures is met by renewable sources such as photovoltaic solar panels or micro-wind turbines integrated on or near the building. This process requires careful calculation and monitoring of energy consumption to ensure the desired balance is achieved year-round.

The implementation of NZEB has broad positive implications, including significant reductions in energy operating costs for building owners and occupants. Beyond the economic benefits, NZEB directly contributes to climate change

mitigation by reducing carbon emissions from the construction and building operations sectors. This aligns with global targets for economic decarbonization and the transition to clean energy, encouraging more environmentally responsible development.

The NZEB concept is expanding toward net-zero carbon buildings, which offset not only their operational energy but also their entire lifecycle carbon footprint, including emissions from construction materials, the building process, and demolition. This involves the use of low-carbon materials, sustainable construction practices, and even carbon sequestration through vegetation. Achieving net-zero carbon requires a holistic approach that encompasses every stage of a construction project, from initial design to the end of a building's lifecycle.

4.7 Implications

This research yields important theoretical and practical implications for the development of sustainable construction in Medan, particularly through the adoption of green and smart building technologies. The study's findings provide a stronger foundation for understanding the dynamics of innovation implementation in the rapidly evolving urban construction sector. The theoretical contribution of this research lies in enriching the literature on the interaction between sustainability concepts, technological innovation, and construction practices (Gallo et al., 2021). This in-depth understanding broadens perspectives on the factors that both drive and hinder the transition to more environmentally friendly and energy-efficient construction practices. The qualitative approach of this case study offers contextual nuances often overlooked in quantitative research, providing holistic insights into how these technologies are adapted within the local environment.

The theoretical implications of this study also lie in highlighting the role of stakeholders in facilitating or hindering the adoption of new technologies. The research underscores the importance of collaboration between government, developers, academics, and the community to create a conducive innovation ecosystem. Understanding the challenges and strategies emerging in the field can aid in the development of a more comprehensive theoretical model of innovation

diffusion in the context of sustainable construction. This study enriches the existing theoretical framework with empirical data from the Medan region, demonstrating how innovation diffusion theory can be applied in specific geographic and socio-economic contexts. The discussion also supports the theory that sustainability is no longer an option, but rather a necessity in modern development.

Practically, this study provides concrete guidance for stakeholders in Medan's construction sector to accelerate the adoption of green and smart building technologies. The proposed strategic recommendations can inform local government policies to encourage the implementation of sustainable building standards. Developers and contractors can leverage these findings to understand market opportunities and potential operational challenges when integrating innovative technologies. The study also highlights the importance of education and capacity building for the construction workforce to enable them to operate and maintain smart building systems. The implementation of these technologies is expected to create a more energy-efficient, ecologically sustainable, and responsive built environment to occupant needs (Gallo et al., 2021).

Higher education institutions and research centers can use the findings of this study as a basis for developing curricula and training programs relevant to the needs of the modern construction industry. The emphasis on the use of local materials and rainwater harvesting systems, as identified in the research, provides direction for the development of products and solutions tailored to local conditions. The findings on regulatory challenges and lack of incentives provide valuable input for developing a legal framework that better supports sustainable innovation. This research contributes to shaping the future of greener and smarter construction in Medan, while supporting the broader sustainable development agenda.

CHAPTER V CONCLUSION

5.1 Conclusion

Based on the results of research and data analysis, the conclusions regarding the implementation of green and smart building technology as an innovation in sustainable construction in Medan are as follows:

1. The implementation of green building technology as a sustainable construction innovation in Medan focuses on resource efficiency and the use of environmentally friendly materials. The construction project adopts rainwater harvesting systems, solar panels, and recycled materials to significantly reduce its carbon footprint. The design plan considers natural lighting and cross-ventilation to minimize dependence on electricity, creating a healthier and more sustainable built environment for city dwellers. Priority is also given to the use of local materials to reduce transportation costs and support the local economy. These efforts demonstrate a commitment to ecologically responsible construction practices.
2. The implementation of smart building technology as a sustainable construction innovation in Medan involves automation systems for operational efficiency and increased occupant comfort. A building management system (BMS) integrates lighting, temperature, and security controls, enabling real-time monitoring and adjustments. The use of smart sensors and the Internet of Things (IoT) in building infrastructure helps optimize energy and water use and improve indoor air quality. These smart technologies support energy efficiency and provide a more responsive experience for building occupants. Optimizing building operations can be achieved through the integration of these digital technologies.
3. The main challenges in implementing green and smart building technologies as sustainable construction innovations include high initial investment costs and a lack of awareness and understanding among stakeholders. The limited availability of skilled personnel for the installation and maintenance of these technologies also poses a significant obstacle. The uneven availability of environmentally friendly materials in local markets and regulations that do

not fully support the adoption of these technologies also slow their development. Resistance to change from conventional construction practices is also a limiting factor.

4. Proposed strategies to increase the adoption of green and smart building technologies in the construction sector involve providing fiscal and non-fiscal incentives for developers and investors. Improving education and training for the construction workforce on these technologies is also essential to build capacity and expertise. Developing clearer regulations and government policy support can accelerate the integration of sustainable practices. Collaboration between government, academia, and industry is expected to create a conducive ecosystem for sustainable construction innovation. All of these efforts are essential to driving the transition to more environmentally friendly and efficient construction.

The transition to sustainable construction should be viewed not simply as a matter of long-term operational cost efficiency, but as a holistic development paradigm that balances ecological, social, and economic dimensions. The Triple Bottom Line concept is relevant here, where project success is measured not only by financial profitability but also by its positive contribution to the environment and society. The implementation of green and smart technologies strengthens the planet and people pillars, creating added value beyond traditional economic calculations. Improving the quality of life for residents and mitigating the impacts of climate change are invaluable social investments.

More broadly, the adoption of this technology also has the potential to create positive disruption in the local construction market, encouraging the emergence of new industries that support the sustainable building ecosystem, such as recycled material manufacturing or energy auditing services. This aligns with the theory of disruptive innovation, where new technologies initially considered niche or expensive can gradually dominate conventional markets through superior value and efficiency. Regulatory developments and incentive schemes should be designed to facilitate such disruption, not only responding to challenges but also proactively shaping the future of the construction industry in Medan. The Smart City framework can serve as a platform for integrating green and smart building

initiatives, creating synergies across sectors and accelerating the achievement of sustainable development goals.

5.2 Suggestions

The suggestions in this study are expected to provide tangible contributions to various parties involved in the development of sustainable construction in Medan. These recommendations are based on research findings regarding the implementation of green and smart building technologies, as well as the challenges that arise in their implementation. The implementation of these innovative technologies is crucial for creating a more energy-efficient and ecologically sustainable built environment. Enhanced collaboration among stakeholders is key to successfully realizing a comprehensive vision of sustainable construction. Through concrete steps, the sustainability of the construction sector can be significantly improved. A holistic approach is needed to ensure the effective and efficient adoption of these technologies.

5.2.1 For Project Developers and Contractors

Project developers and contractors in Medan are advised to be more proactive in adopting green and smart building technologies from the planning stage. Integrating smart energy management systems, such as automated sensors and adaptive climate control, can significantly improve building operational efficiency. The use of environmentally friendly and certified construction materials should also be a top priority. Continuous training for technical teams on green construction practices and smart technology maintenance will ensure human resource competency. Optimizing passive design that utilizes natural lighting and cross-ventilation can reduce reliance on mechanical systems.

Implementing a building life cycle that considers environmental impacts from start to finish will add value. Utilizing renewable energy, such as solar panels, should also be considered to reduce the carbon footprint.

5.2.2 For the Regional Government of Medan City

The Medan City Government is expected to formulate incentive policies that encourage the implementation of green and smart buildings. Providing subsidies or tax breaks for projects that meet sustainability standards can accelerate

the adoption of this technology. Zoning regulations that support sustainable development and limit environmentally damaging construction practices need to be enforced. Providing information and educational platforms on the benefits and best practices of green and smart buildings will increase public awareness. The development of supporting infrastructure, such as smart grids and integrated waste management systems, is also crucial.

Collaboration with academia and the private sector in research and development of innovative technologies can create a more dynamic construction ecosystem. Clear regulations regarding green building certification can ensure quality and accountability.

5.2.3 For Academics and Further Researchers

Academics and researchers can further develop this research by expanding the scope of studies to include the economic and social impacts of green and smart building technologies. Comparative analyses between projects that have adopted these technologies and conventional buildings could provide stronger empirical data. Integrating local cultural factors into green building design could be an interesting research focus. Long-term studies on the energy performance and cost-effectiveness of smart buildings would provide in-depth insights. Developing predictive models for optimizing energy consumption in buildings is also highly relevant.

Research on public perception and readiness for adopting this technology would complement existing perspectives. The use of quantitative or mixed methods could yield more comprehensive and generalized results. Exploring the potential use of artificial intelligence in smart building facility management should also be considered. Analyzing more specific regulatory and policy barriers could be a focus of future research.

5.2.4 For Financial Institutions and Investors

Financial institutions and investors have a crucial role to play in accelerating the transition to sustainable construction by providing innovative financing products that explicitly support green and smart building projects. They are advised to develop "green loan" or "sustainability-linked bond" schemes that offer preferential interest rates or flexible terms for developers committed to green

building certification standards, such as EDGE (Excellence in Design for Greater Efficiencies) or the Green Building Council Indonesia (GBCI). This approach aligns with the principles of "ESG Investing" (Environmental, Social, and Governance), which are gaining global traction, where project sustainability is considered an important indicator of risk and potential long-term returns. They should conduct risk assessments that consider the positive impact of energy and operational efficiency on property valuations, which in turn can increase investment attractiveness.

5.2.5 For Communities and Society Communities and society as

Building end-users play a crucial role in driving market demand for sustainable properties and ensuring the operational sustainability of green and smart buildings. Public education on the direct benefits of these technologies, such as improved indoor air quality, energy cost savings, and improved thermal comfort, must be systematically enhanced. These awareness campaigns can utilize social media, community workshops, and partnerships with non-governmental organizations to disseminate accurate and accessible information. Active participation in building-level recycling and waste management programs, as well as adopting energy-saving behaviors (e.g., turning off lights when not in use or using public transportation), are manifestations of "green user behavior" that is essential for optimizing green building performance. Feedback from end-users on their experiences with smart building technologies can provide valuable data for future improvements and innovations, embodying the concept of "co-creation" in urban development.

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ATTACHMENT

Appendix 1 Research Grid

Designed to systematically guide data collection, ensuring every aspect of the problem statement is addressed through relevant and in-depth information. This structure helps researchers maintain the focus of their study and ensures consistency in data collection from various sources. The following is the research outline that will be used:

Research Grid Table4

No	Research Focus	Subfocus/Aspects Studied	Data Mining Direction	Data Source/Informant	Data collection technique	Instruments/Guidelines
1	Implementation of Green Building Technology	Energy efficiency, water efficiency, waste reduction, use of environmentally friendly materials, indoor environmental quality	Implementation practices, material selection, passive design, renewable energy integration, environmental impact	Architects, contractors, property developers, academics, local government	Interviews, observations, documentation	Interview guidelines, observation guidelines, documentation guidelines
2	Implementation of Smart Building Technology	Integration of automation systems, use of sensors and IoT, utilization of AI, operational efficiency, comfort and safety of residents	The role of IoT and AI, automation systems, operational optimization, sustainability impact	Architects, contractors, property developers, academics, local government	Interviews, observations, documentation	Interview guidelines, observation guidelines, documentation guidelines
3	Challenges in Implementing Green and Smart Building Technologies	High initial costs, interoperability issues, lack of awareness, regulations and policies, availability of	Technical, economic, social, regulatory and market constraints	Architects, contractors, property developers, academics, local government	Interviews, observations, documentation	Interview guidelines, observation guidelines, documentation guidelines

No	Research Focus	Subfocus/Aspects Studied	Data Mining Direction	Data Source/Informant	Data collection technique	Instruments/Guidelines
		materials and technology				
4	Strategies to Increase Adoption of Green and Smart Building Technologies	Regulatory incentives, interdisciplinary collaboration, awareness raising, capacity building, user-centric solutions	Policy recommendations, educational programs, industry-academia partnerships, innovation development	Architects, contractors, property developers, academics, local government	Interviews, observations, documentation	Interview guidelines, observation guidelines, documentation guidelines

Appendix 2 Interview Guidelines

Designed to gather in-depth information from informants regarding the implementation of green and smart building technology as an innovation in sustainable construction in Medan, the interview instrument was structured with open-ended questions to facilitate the exploration of perspectives, experiences, and strategies from practitioners and stakeholders. Data collection through this guideline aims to gain a comprehensive understanding of the issues, challenges, and solutions relevant to the research topic. This guideline serves as a flexible guide, allowing researchers to adjust questions based on informant responses and the dynamics of conversations developing in the field.

Each research focus was broken down into a primary question and follow-up questions aimed at eliciting more detailed and specific information. These questions were formulated to encourage informants to share their knowledge, practical experiences, and personal perspectives regarding the adoption of green and smart building technologies. The interview guide also identified the most relevant types of informants for each aspect of the research, ensuring that the data collected came from credible sources and possessed a strong contextual understanding. This approach is expected to generate rich and authentic qualitative data, supporting in-depth analysis in this study.

Interview Guidelines Table:

Interview Guidelines Table5

No	Research Focus/Subfocus	Data Mining Direction	Main Questions	Follow-up/Probing Questions	Informant
1	Implementation of Green Building Technology	Understand the processes, practices, and basic principles of implementing green building technologies.	How is green building technology implemented in construction projects in Medan?	Can you provide a concrete example of a project that implemented green building? What key principles were considered in its design and construction? What initial challenges did you face, and how did you overcome them?	Architect, Contractor, Environmental Consultant
2	Implementation of Smart Building Technology	Identify the types of smart technologies used, their benefits and challenges.	How is smart building technology applied as an innovation in sustainable construction?	What smart technologies do you use most often? How do they contribute to energy efficiency or resource management? What technical challenges have you encountered during their implementation?	Building Engineer, Property Developer, Project Manager
3	Challenges in Implementing Green and Smart Technologies	Analyze the main obstacles, starting from technical, economic, regulatory, to social aspects.	What are the main challenges faced in implementing green and smart building technologies as sustainable construction innovations?	Are there any challenges related to initial costs, material availability, or a lack of expertise? What role do local government regulations or policies play in addressing these challenges? How has the community	Local Government (Related Agencies), Academics, Property Consultants

No	Research Focus/Subfocus	Data Mining Direction	Main Questions	Follow-up/Probing Questions	Informant
				received this building concept?	
4	Strategies to Increase Adoption of Green and Smart Technologies	Identify solutions, recommendations, and policies that can encourage technology adoption.	What strategies can be proposed to increase the adoption of green and smart building technologies in the construction sector?	How can the government or relevant institutions support increased adoption? Are there effective incentive or education programs? How can collaboration between stakeholders accelerate the implementation of this innovation?	Representatives of Professional Associations (IAI, PII), Financial Institutions, Technology Innovation Developers