EXPLORING SUSTAINABLE PROCESSES IN CONSTRUCTION PROJECTS: EMERGING TECHNOLOGIES AND OPPORTUNITIES

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A project report submitted in partial fulfilment of the requirements for the award of Bachelor of Science Quantity Surveying with Honours

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DECLARATION

I hereby declare that this project report is based on my original work except for citations and quotations which have been duly acknowledged. I also declare that it has not been previously and concurrently submitted for any other degree or award at UTAR or other institutions.

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ABSTRACT

Sustainability and innovation are increasingly shaping the future of the construction industry, with emerging technologies offering new opportunities to enhance environmental, economic, and social performance. This study explores the role of emerging technologies in promoting sustainability in construction projects by identifying key advancements and assessing their practical impacts. Adopting a pragmatic paradigm with a quantitative approach, the study uses a literature review to deductively identify relevant technologies and sustainability potentials, forming the basis for a structured questionnaire. An online survey was conducted among 120 experienced construction professionals, including clients, contractors, and consultants across Malaysia to gather perceptions of the relevancy and effectiveness of smart technologies in sustainability management. The data collected is analysed using descriptive and inferential statistics to derive meaningful insights. Key findings highlight major drivers such as regulatory and market influences, economic and competitive factors, technological advancements, environmental considerations, and strategic motivations. Exploratory factor analysis revealed four underlying factors influencing technology adoption such as policy, innovation and resource-based drivers; environmental and efficiency commitments; market and stakeholder influence; and human awareness and capacity building, offering empirical evidence on industry readiness. The study addresses the gap between technological advancement and sustainability implementation by drawing on industry expertise and identifying key influencing factors. Its novelty lies in presenting a data-driven view of how smart technologies can be strategically integrated to improve sustainability outcomes in construction project management. By aligning industry perceptions with innovation trends, this study offers valuable insights for practitioners and policymakers, supporting a shift toward a more resilient and eco-friendly built environment.

Keywords: Sustainable construction, emerging technologies, resource efficiency, sustainability management, innovation

Subject Area: TD194-195 Environmental Effects of Industries and Plants

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LIST OF SYMBOLS / ABBREVIATIONS

AEC	Architecture, Engineering and Construction
AI	Artificial Intelligence
BIM	Building Information Modeling
CIDB	Construction Industry Development Board
CITP	Construction Industry Transformation Programme
CLT	Central Limit Theorem
CO2	Carbon Dioxide
CSR	Corporate Social Responsibility
EFA	Exploratory Factor Analysis
FDI	Foreign Direct Investment
IoT	Internet of Things
KMO	Kaiser-Meyer-Olkin
LEED	Leadership in Energy and Environmental Design
SMEs	Small and Medium Enterprises
SPSS	Statistical Package for Social Science

α	Cronbach’s alpha value
δ	Standard deviation

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CHAPTER 1

INTRODUCTION

1.1 Background of Study

The global environmental impact has been a subject of intense study and concern among scientists, policymakers, and the general public. Environmental degradation due to human activities is resulting in significant changes to the earth's climate and ecosystems. This degradation encompasses a wide array of issues, including global warming, deforestation, loss of biodiversity, and pollution, all of which have far-reaching consequences for life on Earth (Attfield, 2015). The environmental degradation varies greatly in foreign countries due to differences in industrial practices, regulatory frameworks and levels of economic development. An example which can refer to is China. China has experienced rapid industrialization and economic growth over the past few decades, significantly impacting its environment. The country has seen substantial increases in CO2 emissions, primarily due to its reliance on coal for energy and the expansion of its manufacturing sector (Hou *et al.*, 2021). From 1997 to 2018, China's carbon emissions tripled, contributing to severe air pollution and related health issues. The increase in greenhouse gas emissions has led to more frequent occurrences of acid rain and haze, which threaten both the environment and public health (Hou *et al.*, 2021). Also, in Africa, the interaction between Foreign Direct Investment (FDI) and environmental sustainability is complicated. While FDI can bring economic benefits, it often accompanies increased carbon emissions due to the establishment of energy-intensive industries. Studies indicate that in many African countries, the influx of FDI has been linked to higher CO2 emissions, underscoring the need for sustainable investment practices (Boubacar, Sarpong and Nyantakyi, 2024). The Central and Eastern European countries also grapple with environmental challenges, particularly related to industrial pollution and inefficient waste management. The rapid economic transition in these regions has sometimes led to environmental oversight. For instance, foreign direct investment in these countries has been associated with increased emissions and environmental degradation, calling for improved regulatory frameworks to mitigate these impacts (Christoforidis and Katrakilidis, 2022).

The environmental impacts affect construction sustainability across the globe, including Malaysia. Malaysia, known for its rich biodiversity and extensive natural resources, faces significant environmental challenges (Solaymani, 2023). Rapid urbanization, deforestation, and industrialization have taken a toll on the environment, leading to various ecological and public health issues. In Malaysia, global warming has emerged as a critical environmental issue, exacerbating the country's vulnerability to these extreme weather events. In addition, climate change has led to more frequent and severe adverse weather events, including droughts, floods, and hurricanes (Solaymani, 2023). Emissions from automobiles, manufacturing sectors, construction sites, power stations, and deforestation contribute significantly to climate change by releasing heat-trapping pollutants, primarily carbon dioxide. One of the critical environmental issues is deforestation. As mentioned by Zakaria and Singh (2023), deforestation in Malaysia is driven primarily by the expansion of palm oil plantations and logging activities. These practices have led to significant biodiversity loss and habitat destruction. Malaysia's forests, which are among the world's most biodiverse ecosystems, have been severely impacted. Between 2000 and 2012, Malaysia lost about 14.4% of its forest cover, contributing to the global issue of biodiversity decline and increasing carbon emissions (Zakaria and Singh, 2023). Besides, climate change also poses a severe threat to Malaysia's environment. The country has experienced more frequent and intense weather events, such as floods and droughts, which have had devastating impacts on communities and ecosystems. Climate-related natural disasters have cost Malaysia approximately RM8 billion over the past two decades. The Malaysian government has recognized these challenges and is working towards integrating sustainable practices to mitigate environmental impacts (Zakaria and Singh, 2023). On the other hand, water pollution is another significant environmental issue in Malaysia. The country's rivers and water bodies are often contaminated due to industrial discharge, agricultural runoff, and urban wastewater. Studies have shown that urban and agricultural activities are major contributors to water quality degradation in Malaysia. The main pollutants include heavy metals, chemicals, and organic waste, which adversely affect aquatic ecosystems and human health (Camara, Jamil and Abdullah, 2019).

Due to the environmental impacts based on the above facts, smart technologies are invented these days. The integration of smart technologies in the construction industry is pivotal for achieving sustainability. These technologies enhance not only efficiency and safety but also contribute significantly to mitigating environmental impacts. By adopting smart construction practices, the industry can move towards a more sustainable future, addressing current environmental challenges and improving overall operational efficiencies (Hire, Sandbhor and Ruikar, 2022). Emerging technologies like Building Information Modeling (BIM), Internet of Things (IoT), drones, and AI-driven tools offer transformative benefits by enhancing project management, reducing waste, and improving safety standards. Smart technologies streamline construction processes, reducing time and costs (Y. Chen *et al.*, 2023). For instance, BIM is one of the smart technologies adopted globally which provides comprehensive digital representations of physical and functional properties of structures, encouraging for more accurate planning and coordination. Ullah, Lill and Witt (2019) have stated that this technology can reduce project costs by up to 20% and construction time by 30%, improving efficiency and productivity in the construction industry. While construction sites are hazardous with high risks of accidents and injuries, drones and AI-powered surveillance systems can ensure site safety by providing real-time monitoring and predictive analytics to identify potential hazards (Y. Chen *et al.*, 2023). This proactive approach can reduce accident rates by up to 25%, significantly improving worker safety (Ullah, Lill and Witt, 2019).

While in Malaysia, the integration of smart technologies is similarly advancing. A study by the University of Technology PETRONAS highlighted the significant role of cloud computing in promoting sustainable development in small construction projects. The research identified critical success factors such as cost, quality, time management, planning success, organizational success, and effective communication and coordination as essential for the successful implementation of these technologies (Waqar et al., 2023). Additionally, the Construction Industry Development Board (CIDB) Malaysia has been actively promoting the adoption of smart technologies to drive the construction industry towards sustainability and higher productivity. This includes the implementation of Industry 4.0 strategies and digital construction techniques to streamline processes and reduce the carbon footprint of construction activities (CIDB, 2020).

In short, the adoption of smart technologies in construction is not only about improving operational efficiencies but also about addressing broader environmental and sustainability challenges. With technologies like BIM, IoT, and cloud computing, the industry can achieve significant reductions in resource consumption, minimize waste, and improve overall project sustainability, thereby contributing to the global goals of reducing greenhouse gas emissions and enhancing environmental stewardship.

1.2 Problem Statement

The construction industry is a vital contributor to national development, but it also poses significant environmental challenges due to its high consumption of natural resources and its contribution to carbon emissions, waste generation, and energy use. In response, the concept of sustainable construction has gained prominence globally, with numerous studies exploring green building practices, energy-efficient designs, life-cycle assessments, and eco-friendly materials as strategies to reduce the environmental footprint of construction activities (Darko & Chan, 2016; Zhao et al., 2020).

In the Malaysian context, the Construction Industry Development Board (CIDB**)** has played a central role in driving sustainability through policy and industry frameworks. One of the key initiatives is the Construction Industry Transformation Programme (CITP) 2016–2020**,** which outlines four strategic thrusts: Quality, Safety and Professionalism; Environmental Sustainability; Productivity; and Internationalisation. The Environmental Sustainability thrust specifically emphasizes the adoption of sustainable practices and the integration of emerging technologies to support green construction and reduce the sector's carbon footprint. CIDB's Green Infrastructure initiatives and the Sustainable Construction Excellence Centre (Mampan) reflect ongoing efforts to align the industry with national and global sustainability goals.

Despite these strategic efforts, the actual implementation and integration of emerging technologies—such as Building Information Modeling

(BIM), Internet of Things (IoT), Artificial Intelligence (AI), and Digital Twins—into sustainable construction practices remains limited. Previous studies in the Malaysian construction industry have shown a growing awareness of sustainable principles and the potential of digital technologies, yet most research treats these two areas independently. For example, while BIM adoption has been explored for productivity gains and project coordination (CIDB Malaysia, 2020), its potential to support life-cycle sustainability assessments or real-time environmental performance tracking is often underutilized or poorly integrated into current workflows.

Globally, similar gaps are observed. Although the literature extensively covers sustainable construction and technological innovation as separate themes, few integrative studies explore how emerging technologies can actively drive and enhance sustainability performance throughout the project lifecycle (Sacks et al., 2020; Li et al., 2022). Moreover, empirical studies providing real-world data on this integration are scarce, particularly in the Malaysian context, where challenges such as high implementation costs, lack of skilled personnel, and limited digital infrastructure persist (Maqbool et al., 2023).

Additionally, while the CITP outlines a clear roadmap**,** its targets for sustainable construction, such as increasing the number of green-certified buildings or achieving productivity gains through technology, have only been partially realized. According to CIDB's progress reports, adoption rates of technologies like BIM and sustainable materials remain below expectations, particularly among small and medium-sized enterprises (SMEs), which dominate the Malaysian construction landscape.

This highlights a critical research gap which is the lack of integrative frameworks, case studies, and empirical evidence on how emerging technologies can be effectively deployed to meet sustainability objectives as envisioned by the CITP and CIDB guidelines. Without a deeper understanding of the synergies between digital transformation and sustainability, the industry risks failing to meet national goals for green construction and environmental resilience. Thus, this research aims to explore and evaluate the integration of emerging technologies within sustainable construction processes in Malaysia, guided by the policy frameworks of CIDB and the aspirations of the CITP. The study will identify existing gaps, opportunities, and practical strategies to enhance sustainability through digital innovation, with the goal of contributing to a more environmentally responsible and technologically advanced construction industry in Malaysia.

In summary, the construction industry faces growing pressure to adopt sustainable practices due to its significant environmental impact. While global and Malaysian studies have explored sustainable construction methods and the use of emerging technologies like BIM, IoT, and AI, most research treats these areas separately. In Malaysia, the Construction Industry Transformation Programme (CITP) and CIDB have emphasized sustainability and digital innovation as national priorities. However, the integration of emerging technologies to support sustainability goals remains limited in practice, particularly among SMEs. Although the CITP outlines strategic goals for green construction and technological advancement, the adoption of integrated solutions is still fragmented. Research lacks comprehensive frameworks and real-world case studies showing how technologies can enhance sustainability across the full construction lifecycle. This creates a gap in both academic understanding and industry implementation. Therefore, this study seeks to explore how emerging technologies can be effectively integrated into sustainable construction practices in Malaysia, aligned with CIDB and CITP priorities, to support environmental and technological transformation in the industry.

1.3 Research Aim

This study aims to investigate how emerging technologies contribute to the advancement of sustainable practices in the construction industry, with a focus on understanding their transformative potential and implications for long-term industry development.

1.4 Research Objectives

This dissertation is prepared to serve the following purposes:

I. To identify the opportunities of emerging technologies on sustainability in the construction industry.

II. To examine the drivers of emerging technologies that improve construction sustainability.

III. To evaluate the challenges of adopting emerging technologies in the construction industry.

1.5 Research Methodology

This study adopts a quantitative research approach to explore sustainable practices in the construction industry through the adoption of green technologies. Primary data will be collected via an online questionnaire targeting 500 construction professionals, including developers, consultants, and contractors, with a minimum of 30 respondents per group to ensure a 24% response rate.

The questionnaire is the main data collection tool, and the responses will be analyzed using Cronbach's Alpha**,** Mean and Standard Deviation**,** Kruskal-Wallis Test**,** Spearman's Correlation**,** and Factor Analysis**.** Secondary data from journals, books, literature reviews, and news articles will support and enrich the findings.

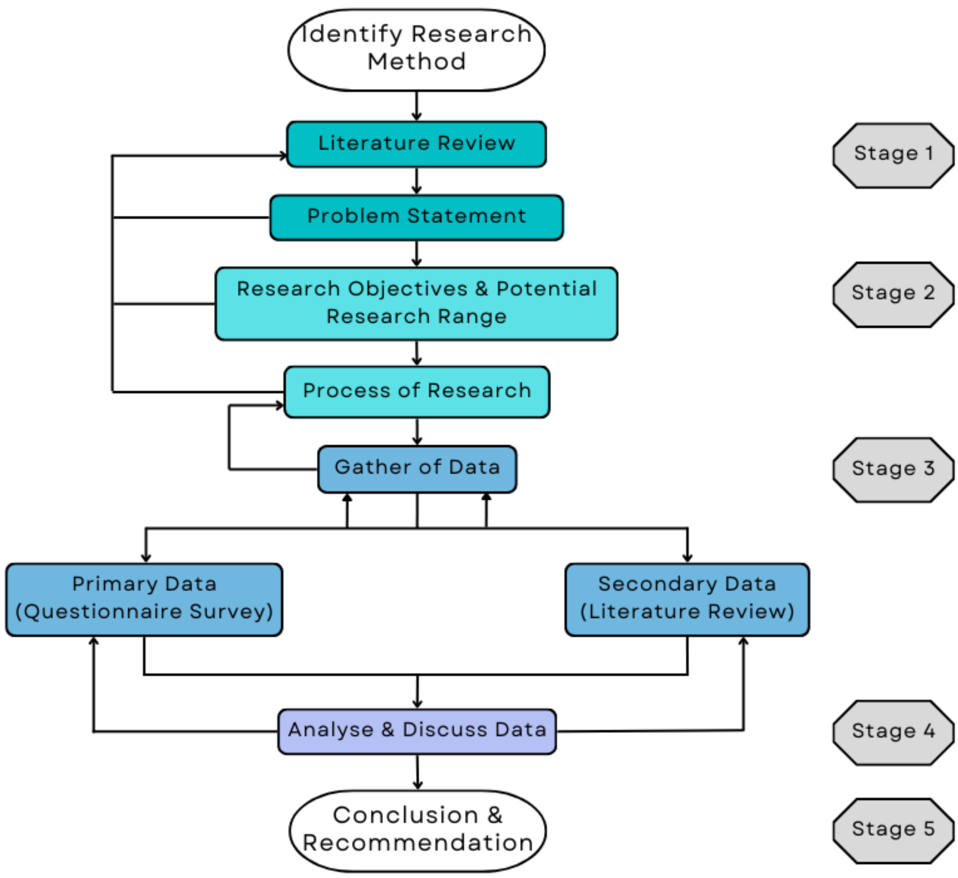

Figure 1.1: Research Plan

1.6 Research Scope

This research focuses on investigating how emerging technologies are being integrated into sustainable construction practices within the Malaysian construction industry. The study primarily targets construction professionals and key stakeholders such as clients, consultants, and contractors who are directly involved in various aspects of construction projects. These participants are selected based on their capacity to influence decision-making, implement sustainable strategies, and adopt technological innovations within their respective roles.

Geographically, the research centers on Klang Valley, which is recognized as one of the fastest-growing and most urbanized regions in Malaysia (Salim et al., 2023). Klang Valley serves as a significant hub for construction activities, offering valuable insights into current industry practices, technology adoption, and sustainability challenges. To ensure broader data representation and enhance the generalizability of the findings, the study also includes participants from other regions across the country, including the Northern region, Southern region, East Coast, as well as Sabah and Sarawak. This nationwide coverage allows the study to capture a more diverse range of perspectives and practices from different regional contexts.

The research adopts a sample size of 120 respondents, with an aim to secure at least 30 participants from each of the three main stakeholder groups—clients, consultants, and contractors. This approach ensures a balanced and comprehensive view across different segments of the construction industry. The study is designed to assess sustainable practices implemented throughout the entire construction project life cycle. This includes the design and planning phase, where sustainable concepts and materials are selected; the procurement stage, where green procurement practices may be applied; the construction phase, which involves resource efficiency and waste management on-site; the operation and maintenance phase, focusing on building performance and energy usage; and finally, the decommissioning or end-of-life stage, which considers demolition practices and material reuse. By examining all phases of the project life cycle, the study aims to provide a holistic understanding of sustainable construction and identify where technology has the greatest impact.

In terms of technological scope, the study focuses on emerging technologies that have been introduced or increasingly adopted within the last five to ten years. These include innovative digital tools and systems that are considered to have significant potential to improve sustainability outcomes in construction. Among the technologies examined are Building Information Modeling (BIM), Internet of Things (IoT), Artificial Intelligence (AI), Digital Twins, drones, automation and robotics, as well as 3D printing and data analytics platforms. These technologies are evaluated in terms of their level of implementation, perceived benefits, and the challenges they present in real-world construction settings.

Overall, this study seeks to understand how these emerging technologies contribute to sustainable construction across all stages of the project life cycle and within different regions of Malaysia, in alignment with national efforts such as those led by CIDB and the goals outlined in the Construction Industry Transformation Programme (CITP). The scope is intentionally broad to capture the complexity and interconnectedness of technology and sustainability in the contemporary construction industry.

1.7 Outline of the Report

The scope of this study will be structured into five chapters. Each chapter covers various subjects that are all relevant to the topic of this dissertation. All the chapters are arranged and presented in the following sequence.

Chapter One: Introduction

Among others, this introduction chapter touches on the approach of technology to construction projects while sustaining the construction industry Over and above that, the problem statement, research aim and objectives, research methodology and work plan, research scope and chapter outline have been demarcated.

Chapter Two: Literature Review

This chapter merely concentrates on the literature review on the relevant subjects that are regarding the title of this dissertation. This report will cover the opportunities of green technologies leading to sustainable construction processes and the drivers that drive the construction projects greener while challenges will also be discussed in the third part of this chapter. The primary aim of this chapter is to advocate the pros of using green technologies and enable the industry to adopt these technologies in the future.

Chapter Three: Research Methodology

This chapter primarily covers the research technique and method used when collecting data. Research data can be divided into two parts which are qualitative and quantitative. All the relevant data for this project were mainly obtained from two different sources: namely, primary data and secondary data. Questionnaires will be distributed to respondents to collect primary data, while secondary data will be collected from journals.

Chapter Four: Result and Discussions

This chapter primarily mentioned the evaluation and analysis of data derived from the participants. Chapter 4 provides a comprehensive analysis and interpretation of the questionnaire data. It delves into examining the collected responses to deepen the understanding of the research topic and to achieve the study's objectives.

Chapter Five: Conclusion and Recommendations

Generally, this chapter comprises the overall conclusion from the research findings of this project. This chapter will outline the limitations and recommendations for future research and raise awareness of the opportunity of emerging green technology in the construction industry.

1.8 Summary

To sum up, the main objective of this research was to explore sustainable processes by using emerging technologies and their opportunities in the construction industry. After studying the research background, environmental impacts have been highlighted as a major issue of current construction conditions. Hence, the research aims and objectives are established to explore the opportunities of using emerging technologies to create a more sustainable construction process while mitigating ecological issues.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

In this chapter, prevailing theories and past studies from journals by other researchers are to be studied and reviewed. This chapter start out with a brief introduction to sustainability and emerging technologies to create sustainability to enhance the readers' understanding of the term "sustainability" in the construction industry. After reviewing the related studies, the opportunities and the drivers for using emerging technologies in the current construction industry. Furthermore, this chapter will also explore the possible challenges that hamper the use of emerging technologies in the construction industry by analysing the earlier related research.

2.2 Definitions

Table 2.1: Definition of Construction Sustainability

Terms	Definitions	Authors
Sustainability	"Sustainability is defined as the practice of maintaining processes in a way that avoids the depletion of natural resources, thereby supporting long-term ecological balance."	(Mensah, 2019, p. 5)
Construction Sustainability	"Sustainable construction not only requires ecological or environmental sustainability matters to be addressed, but also requires economic such as competition, costs, and construction time, social such as health and safety, local community needs, and technical sustainability."	(Mavi et al., 2021, p. 1)

Based on Table 2.1 above, Mensah (2019) elaborates on the term "sustainability" by emphasizing the importance of balancing ecological, social and economic dimensions to ensure the longevity of natural resources. Mensah explains that sustainability is not just about environmental preservation but also involves creating systems that can support human life and economic activities without jeopardizing future generations' ability to fulfil their expectations. Mensah (2019) also highlights that sustainability is integral to achieving sustainable development, which seeks to harmonize the relationship between humans and their environment for long-term viability and resilience.

In contrast, Mavi et al. (2021) explore the concept of sustainability in construction projects, highlighting that achieving sustainability involves a comprehensive approach that integrates environmental, economic, social and technical dimensions. They emphasize that sustainable construction isn't limited to minimizing environmental impacts but also includes optimizing economic outcomes such as reducing costs, enhancing competitiveness, and ensuring timely project delivery. Moreover, they stress the importance of social sustainability, which involves protecting the health and safety of workers, addressing the needs of local communities, and ensuring that construction projects contribute positively to social welfare. The authors also underline the significance of technical sustainability, which requires the use of innovative and durable materials and technologies that ensure the long-term viability and resilience of construction projects. This multi-faceted approach ensures that construction projects are not only green but also economically viable, socially beneficial, and technically robust.

2.3 Emerging Technologies in Creating Sustainable Construction Industry

Emerging technologies include a broad range of innovative tools and methods, such as BIM for precise project planning and resource management, 3D printing for reducing material waste and construction time and smart building technologies for optimizing energy efficiency and monitoring environmental impact. These technologies play an important part in transforming the construction industry towards sustainability (Shen, Zhang and Zhang, 2017). The use of emerging technologies is critical to achieving sustainability in the construction industry because they enable more efficient resource use, reduce wastage, minimize carbon emissions and enhance the overall environmental performance of buildings (Lu *et al.*, 2017). Emerging technologies can be implemented across different construction projects, including residential, commercial and infrastructure developments in both and rural areas. This widespread application ensures that sustainability goals are achieved at different scales and contexts which contributes to global sustainability efforts (Ofori, 2015). Emerging technologies should be integrated at the earliest stages of the construction process, particularly during the planning and design phases. Early adoption allows for the incorporation of sustainable practices from the outset by reducing environmental impacts throughout the lifecycle of the building. Continual application of these technologies during the construction and maintenance phases further ensures that sustainability goals are consistently met (Lu *et al.,* 2017). The stakeholders are the most suitable individuals to use emerging technologies in leading the sustainable construction industry including architects, engineers, construction managers and policymakers. These professionals are well-positioned to integrate sustainable practices through the use of such emerging technologies (Olawumi and Chan, 2018). To effectively use emerging technologies, stakeholders must invest in education and training, adopt supportive policies and encourage collaboration across the construction supply chain. This comprises the use of technology across all stages of construction, encompassing design, material choice, construction techniques, and building operations, to prioritize sustainability at each step (Gan *et al.*, 2015a).

2.4 Types of Emerging Technologies

2.4.1 Building Information Modeling (BIM)

The first applications of BIM were aimed at enhancing the cooperation between different entities involved in construction projects and at overcoming the problems related to the use of two-dimensional drawings. The pioneers of BIM technology understood that it could improve that which frequently results in time and money losses (Karasaka and Ulutas, 2023).

Throughout the 2010s, BIM technologies advanced, and the integrated modelling software underwent advancements and received additions such as 3D, real-time data sharing and compatibility with other tools used in construction management. This evolution was due to the improvement of software capability and the complexity of construction projects that have grown. Since governments and industry organisations from different parts of the world embraced the idea of BIM, standards and guidelines for the implementation of BIM have been required. (Zhang *et al.*, 2023).

Today, BIM is used not only for design but also at the construction and operation stages in the life cycle of a building. It makes it possible to approximate construction and plan scenarios of different project teams to enhance designs and working models. In addition, BIM can interface with other technologies such as the IoT and AR which has broadened its function and made building smarter and more sustainable (EL Mounla *et al.*, 2023).

2.4.2 3D Printing

3D printing, or additive manufacturing (AM), is a technology that manufactures three-dimensional objects from a digital file by layering materials sequentially until the final shape is achieved. This technology utilizes a range of materials, such as polymers, metals, and ceramics to create intricate designs that would be difficult or impossible to construct using typical production processes. The primary benefit of 3D printing is its ability to create complicated shapes with great precision and minimum waste (Prashar, Vasudev and Bhuddhi, 2023; Ukobitz, 2020).

The invention of 3D printing may be traced to the late 1980s and early 1990s. Initially, it was developed to facilitate rapid prototyping, allowing designers and engineers to create prototypes quickly and efficiently. The primary motivation behind its development was to shorten the product development cycle, reduce costs, and enable the creation of prototypes that closely mimic the final product. This feature is extremely beneficial in industries such as aerospace, automotive, and healthcare (Prashar, Vasudev and Bhuddhi, 2023). Thus, the initial efforts focused on creating simple building components, such as walls and panels, using concrete and other cementitious materials. These early projects demonstrated the potential for reducing construction time and material waste while enabling more complex and custom designs (Kazemian, Seylabi and Ekenel, 2022; Baigarina, Shehab and Ali, 2023).

2.4.3 Prefabrication

Prefabrication in construction is manufacturing building components at a factory and transporting them to the construction site for assembly. This method also known as off-site or industrialized construction which is to address inefficiencies, high material wastage, and unpredictable site conditions associated with traditional construction methods (Gibb and Isack, 2018). Prefabrication's roots can be traced back to early 20th-century efforts to address the limitations of traditional construction methods. These limitations included labour-intensive processes, lengthy project durations, and inconsistent quality. Early adopters saw prefabrication as a solution to streamline production and improve consistency. For example, during the post-World War II housing shortage, prefabrication provided a rapid means of constructing homes to meet the urgent demand for housing (Moradibistouni, Vale and Isaacs, 2019; Fernandez-Ordonez Hernandez, 2018).

The invention and adoption of prefabrication have been driven by the need for greater efficiency and control in the construction process. In a factory environment, components can be produced with high precision and consistency, which is harder to achieve on-site due to varying environmental conditions. The controlled setting also allows for the use of advanced manufacturing techniques and better-quality control, resulting in more durable and reliable building components (Li *et al.*, 2017).

2.4.4 Robotics and Automation

Robotics and automation in construction began to gain attention in the late 20th century, primarily aimed at improving productivity and reducing the dependency on manual labour. The early adoption was marked by using automated machines for repetitive tasks such as bricklaying, concrete placement, and rebar tying. These initial applications were motivated by the need to address the labour-intensive nature of construction work and to mitigate the risks associated with it, such as injuries and fatalities (Liu et al., 2024; Bademosi and Issa, 2022).

As technology advanced, so did the capabilities of construction robotics. The integration of more sophisticated robotics and automation systems in the 21st century has been propelled by developments in artificial intelligence (AI), machine learning, and sensor technologies. These advancements have enabled the creation of robots that can perform complex tasks, such as site surveying, autonomous machinery operation, and real-time data collection and analysis. For example, automated bricklaying robots and drones for aerial surveying are now common on construction sites (Bademosi and Issa, 2022).

2.4.5 Smart Building Technologies

The invention and implementation of smart technologies in the construction industry, including artificial intelligence (AI) and the Internet of Things (IoT), are driven by several critical factors aimed at addressing long-standing challenges and enhancing efficiency, safety, and sustainability. According to Kato et al. (2023), smart technologies significantly improve construction project management through data collection and analysis in real-time. IoT sensors can monitor various aspects of the construction site, including equipment health and the surrounding environment, which results in predictive maintenance and reduced downtime. AI algorithms analyse the large amount of data collected to optimize resource allocation, schedule tasks more effectively, and predict project timelines more accurately. This leads to better project management and execution, minimizing delays and cost overruns.

The early development of smart building technologies began with the integration of automated control systems for heating, ventilation, and air conditioning (HVAC) systems. These systems aim to optimize and reduce energy use while enhancing comfort levels within buildings. The initial push for these innovations was largely driven by the rising energy costs and the need for sustainable building practices (Mckoy et al., 2023; Simpeh et al., 2022).

2.4.6 Drones

The historical invention of drones, also known as unmanned aerial vehicles (UAVs), in the construction industry, marks a significant shift towards advanced technological integration aimed at enhancing project efficiency, safety, and data accuracy. Initially, drones were utilized in military applications, but their adaptation into civilian sectors, including construction, began in earnest over the last decade, driven by advancements in drone technology and the need for innovative solutions in construction project management (Giordan et al., 2020; Choi et al., 2023).

The early integration of drones into the construction industry was primarily driven by their capability to provide aerial perspectives that were previously difficult, costly, or dangerous to obtain. Early adopters used drones for site surveying and mapping, leveraging their ability to capture clear images and generate detailed topographic maps quickly and accurately. This capability significantly reduced the time and cost associated with traditional land surveying methods (Choi et al., 2023; (Szóstak *et al*., 2023).

2.4.7 Personal Protective Equipment (PPE) Technology

The invention of personal protective equipment (PPE) technology in the construction industry has been driven by the need to ensure worker safety and health, reduce accident rates, and comply with stringent occupational safety regulations. Over the past decade, advancements in PPE technology have significantly improved its effectiveness and user acceptance in construction environments. One of the primary motivations behind the development of advanced PPE technology is the high incidence of workplace injuries and fatalities in the construction industry (Rashidi et al., 2024; Márquez-Sánchez et al., 2021; Nguyen et al., 2024).

According to research, construction workers are exposed to various hazards, including falls, electrical shocks, and exposure to harmful substances. These risks necessitate reliable and innovative PPE solutions to protect workers effectively (Alaloul *et al.*, 2020). Therefore, the invention and advancement of PPE technology in the construction industry are vital for safeguarding workers and ensuring compliance with safety standards. These technological innovations not only enhance the effectiveness of PPE but also promote a culture of safety and continuous improvement in construction practices.

2.4.8 Hydrogen Technology

The evolution of hydrogen technology in the construction industry has been driven by the urgent need to decarbonize and enhance sustainability. The historical progression of this technology can be traced through several key milestones over recent decades. Initially, the concept of a hydrogen economy emerged in the early 1970s, envisioned as a sustainable alternative to fossil fuels. This period saw hydrogen primarily being explored for its potential as a clean energy carrier that could utilize nuclear and solar energy efficiently (Yap and McLellan, 2023). The oil crisis of the 1970s further spurred interest in alternative fuels, including hydrogen, as nations sought to reduce dependence on oil.

During the late 20th and early 21st centuries, research and development in hydrogen technology gained momentum, driven by advances in fuel cell technology and a growing awareness of climate change. The Kyoto Protocol and subsequent international agreements underscored the need for cleaner energy solutions, pushing hydrogen to the forefront of energy research (Xue *et al.*, 2014). Technological advancements in electrolysers and storage systems also made hydrogen a more viable alternative for various applications, including in the construction sector.

Recent years have witnessed the integration of hydrogen technology into the construction industry, driven by both regulatory pressures and the industry's sustainability commitments. Construction companies are increasingly adopting hydrogen-powered machinery, such as excavators and cranes, which significantly reduce onsite emissions. Additionally, hydrogen is being explored as a potential energy source for off-grid construction sites, where traditional power sources are not feasible. The versatility and environmental benefits of hydrogen make it an attractive option for the industry (Deng *et al.*, 2023).

2.4.9 Mobile and Cloud Technology

Mobile technology has significantly impacted the construction industry by enhancing communication and on-site management. Historically, the construction industry relied heavily on paper-based methods and manual processes, which were time-consuming and prone to errors. The introduction of mobile technology has allowed for real-time communication, improved accuracy in data collection, and increased productivity. Mobile devices enable project managers and workers to access and update project information on the go, thus reducing delays and improving efficiency (Ukobitz, 2020).

Cloud technology has transformed how data is stored, accessed, and shared in the construction industry. Before its adoption, construction projects often faced challenges related to data silos, where information was not easily accessible to all stakeholders. Cloud-based solutions offer a centralized platform for storing project data, which can be accessed by authorized personnel from anywhere at any time. This has facilitated better collaboration among project teams, streamlined workflows, and ensured that everyone has the most up-to-date information (Ukobitz, 2020).

2.4.10 Smart Grids and Energy Storage

Smart grids have revolutionized the traditional electrical grid by incorporating advanced communication and control technologies. These grids facilitate two-way communication between consumers and utility companies, enabling real-time monitoring and control of energy use. The concept of smart grids emerged to address the limitations of conventional grids, which struggled with inefficiencies, lack of flexibility, and vulnerability to outages. According to Alotaibi et al. (2020), the integration of information and communication technologies (ICT) into power systems began to transform energy management. Smart grids were designed to enhance the reliability and efficiency of electricity distribution, support the integration of renewable energy sources, and improve grid technologies, including the development of advanced metering infrastructure (AMI), demand response (DR) systems, and distributed energy resources (DERs) (Habbak *et al.*, 2023).

Energy storage systems (ESS) are significant for the effective implementation of smart grids. They address the unpredictability of renewable energy sources like solar and wind by storing excessive energy during periods of low demand and releasing it when demand is high. The development of ESS has been pivotal in stabilizing the grid and ensuring a consistent energy supply (Alotaibi et al., 2020). Historically, energy solutions such as pumped hydro storage have been used for decades. However, recent developments in technologies have resulted in more sophisticated and versatile storage options, including lithium-ion batteries, flow batteries, and supercapacitors. These innovations have enhanced the efficiency, capacity and lifespan of energy storage systems, increasing the chances of becoming widely adopted in smart grids (Habbak *et al.*, 2023).

2.4.11 Digital Twins

Historically, the adoption of digital twins in construction stems from the broader integration of digital technologies in various industries. Initially, construction relied heavily on Building Information Modeling (BIM), which provided detailed 3D models of buildings. However, BIM lacked real-time operational data and the dynamic capabilities offered by digital twins. By integrating real-time data through sensors and IoT devices, digital twins can provide continuous updates on the status and performance of construction projects, enabling more effective decision-making and project management (Bilal et al., 2016; Qi et al., 2018).

One of the primary drivers behind the development and adoption of digital twins in construction is the need for improved project efficiency and risk management. Digital twins allow for the simulation of various scenarios, which can help in identifying potential issues. This effective approach not only enhances safety but also helps in optimizing resource allocation and reducing costs. For instance, developers can use digital twins to test emergency response strategies or evaluate the impact of different design choices on project timelines and budgets (Bilal *et al.*, 2016).

2.4.12 Water-Efficient Technologies

The development of water-efficient technologies in the construction industry has been a critical response to growing concerns about water scarcity, environmental sustainability, and the need for resource-efficient building practices. This evolution has been driven by both technological advancements and regulatory frameworks aiming to mitigate water usage and its associated impacts (Geetha Varma, 2022; Marinoski, Rupp and Ghisi, 2018). Water-efficient technologies in construction have their roots in traditional practices of water conservation and management, which have been modernized through innovative technologies and smart systems. Early efforts primarily focused on improving the efficiency of water fixtures and incorporating basic rainwater harvesting systems. These initial steps laid the groundwork for more sophisticated approaches seen today (Teston et al., 2022; Campisano and Modica, 2016).

Modern water-efficient technologies encompass a broad range of systems designed to minimize water usage. These include smart water meters, greywater recycling systems, rainwater harvesting, and advanced irrigation systems. Smart water meters, for example, provide real-time data on water consumption, enabling the detection of leaks and unnecessary usage, which helps reduce overall water consumption (Geetha Varma, 2022). Greywater recycling systems filter and recycle water from showers, sinks, and laundry for gardening and toilet flushing. This not only reduces the demand for freshwater but also decreases the volume of wastewater requiring treatment. Rainwater harvesting systems capture and store rainwater for non-potable uses, thereby conserving treated water for essential purposes (Marinoski, Rupp and Ghisi, 2018).

2.4.13 Hybrid Renewable Energy System

The historical invention of hybrid renewable energy systems (HRES) in the construction industry marks a pivotal shift toward sustainable and reliable energy sources. These systems integrate multiple renewable energy sources, such as solar, wind, hydro, and biomass, often coupled with energy storage measures like batteries or hydrogen storage. This hybrid approach aims to mitigate the intermittency and reliability issues that are common with single-source renewable energy systems (Miglioli *et al.*, 2023).

The development of HRES was initially driven by the limitations of individual renewable energy sources. For instance, solar and wind power often depend on weather conditions and time of day, leading to inconsistent energy supply. The early HRES aimed to create a more stable and reliable power supply, essential for the consistent operation of buildings and infrastructure by combining different resources. This combination allowed for more continuous and reliable energy output, addressing the fluctuating nature of renewable energy sources (Miglioli *et al.*, 2023).

Gradually, advancements in technology have significantly improved the efficiency and feasibility of HRES. Modern systems incorporate advanced control and optimization algorithms to manage the integration and distribution of energy from various sources effectively. These systems can dynamically adjust to unpredictable environmental conditions and energy demands, optimizing efficiency and reducing waste. The integration of smart grids and real-time data analysis has further enhanced the performance and reliability of HRES (Hassan *et al.*, 2023).

2.4.14 Carbon Capture and Storage (CCS)

The early 2010s marked significant progress in the deployment of CCS technologies. By 2014, CCS was already being implemented in various pilot projects globally. A pivotal moment came with the ratification of the Paris Agreement in 2015, which emphasized the role of CCS in achieving climate targets. This period saw increased investment in CCS projects, especially in industries with hard-to-abate emissions, such as cement and steel manufacturing One notable example are the Petra Nova project in the United States, which became the world's famous carbon capture system on a coal-fired power plant. Operational since 2016, it demonstrated the viability of integrating CCS technology into current facilities (Shen et al., 2022).

The technological advancements in CCS during this period include improvements in the efficiency of CO_2 capture processes, the development of robust transport infrastructure, and the refinement of storage techniques. Geological storage, the most common method, involves injecting CO_2 into deep saline formations or depleted oil and gas fields. These advancements have been crucial in addressing the technical and operational challenges associated with large-scale CCS deployment in the construction industry (Yasemi *et al.*, 2023)

2.5 Opportunities of Emerging Technologies on Sustainability in the Construction Industry

2.5.1 Enhanced Collaboration and Efficiency

Building Information Modeling (BIM) is a cornerstone technology that enhances collaboration and efficiency in construction projects. BIM involves creating a digital representation of a building's physical and functional characteristics, which can be shared among all stakeholders, including architects, engineers, and construction managers. The collaborative nature of BIM allows all parties to work from the same data, minimizing errors and reworking (Lu, Won and Cheng, 2016). Besides, cloud technology supports the integration of Building Information Modelling (BIM), which plays a crucial role in sustainability design and planning. By using BIM in the cloud, architects and engineers can collaborate more effectively, exploring different design options and their sustainability impacts (Mavi *et al.*, 2021b).

Besides, digital twins are virtual representations of tangible resources that provide real-time data and analytics on the performance, operation, and condition of those assets. In the construction industry, digital twins enable enhanced collaboration and efficiency by allowing stakeholders to visualize and simulate various scenarios before execution. This capability helps in identifying potential issues and optimizing processes, thereby reducing the risk of errors and delays. Additionally, digital twins facilitate continuous monitoring and management of assets throughout their lifecycle, ensuring that maintenance and operational decisions are based on accurate and up-to-date information (Fuller *et al.*, 2020). This holistic approach to asset management enhances the efficiency and sustainability of construction projects.

Furthermore, drones can monitor the progress of construction projects in real-time, allowing for better scheduling and coordination, which prevents unnecessary delays and reduces the likelihood of rework. They are used for site surveys, progress monitoring, and inspections, providing high-resolution aerial imagery and data that can be shared among project stakeholders. For construction projects that involve large-scale landscaping or integration with agricultural areas, drones offer precise mapping and analysis capabilities. This precision aids in the efficient planning and implementation of green spaces, which are essential for sustainable urban development (Zhu *et al.*, 2022).

2.5.2 Reduction of Materials Waste

3D printing, also known as additive manufacturing, is a cutting-edge technology with the potential to minimize material waste in the construction sector. Unlike traditional building processes, which frequently entail cutting and moulding materials, 3D printing produces structures layer by layer, utilizing simply the quantity of material required. This process minimizes waste by ensuring that excess materials are not produced (Buswell *et al.*, 2018).

Apart from that, robotics and automation play a significant role in reducing material waste in construction. Automated systems can carry out tasks with high accuracy and consistency, reducing errors and the need for rework. For example, robotic bricklaying systems can lay bricks with exact precision, minimizing the wastage of mortar and bricks. Similarly, automated cutting and assembly machines can maximize the use of raw materials, making sure that components are cut to the exact dimensions required, thus reducing off-cuts and waste (Bock, 2015). This level of precision is difficult to achieve with manual labour and results in significant resource savings. According to a study, implementing robotics in construction can lead to a reduction in material waste by up to 30% (Zhu *et al.*, 2022).

Besides, prefabrication helps in reducing material waste. According to Pittau et al. (2017), traditional construction methods often result in substantial waste due to inefficiencies and errors during on-site construction. Prefabrication, by contrast, allows for precise control over the manufacturing process, minimizing waste through exact material measurements and efficient reuse of offcuts. This will lead to a significant decrease in the overall environmental impact of construction projects. On the other hand, drones can also help optimize the use of materials by providing accurate measurements and monitoring material stockpiles. This precision reduces over-ordering and minimizes waste (Zhu *et al.*, 2022).

2.5.3 Improved Energy Efficiency

Prefabrication is one of the most energy-efficient technologies in the construction industry. Prefabrication is constructing the elements such as walls in advance rather than constructing on-site. As prefabrication does not require casting on-site, traditional construction processes such as concreting will be eliminated, and the workers are required to ensure that the prefabricated modules are placed correctly. As a result, it has proven to enhance energy efficiency while mitigating possible construction errors and risks as well as reducing manpower and material waste. (Loizou et al., 2021).

Another emerging technology that enhances energy efficiency is the embarked of 3D printing in the construction process. 3D printing enables the creation of complex geometric shapes that are hard to achieve with conventional methods and produces structures with improved thermal performance. For instance, walls can be printed with internal cavities that act as insulators, minimizing the need for additional insulation materials and improving the energy efficiency of the building. The flexibility of 3D printing also supports the customization of building designs to optimize natural light and ventilation, further reducing energy consumption. Customizable designs can incorporate features such as strategically placed windows and airflow channels, which enhance the building's passive cooling and lighting capabilities, thereby lowering the dependency on artificial lighting and HVAC systems (Rahmawati et al., 2022).

Additionally, BIM supports the implementation of sustainable design practices by enabling detailed simulations and analyses of building performance. This includes energy modelling, daylight analysis, and lifecycle assessment, which are crucial for optimizing building designs to meet sustainability targets. By integrating green technology within the BIM framework, project teams can evaluate the environmental impact of different design options and make informed decisions to improve the building's energy efficiency and minimize its carbon footprint (Li *et al.*, 2022).

On the other hand, robotics and automation improve energy efficiency during construction. Automated machinery can perform tasks more quickly and continuously than human labour, reducing the overall time and energy consumed on-site. This efficiency not only speeds up project completion but also decreases the carbon footprint associated with prolonged construction activities (Ramli, Azizi and Thurairajah, 2024).

Furthermore, the integration of CCS with other sustainable energy systems can lead to improved energy efficiency and resource utilization in construction. For example, combining CCS with renewable energy sources can create a more balanced and reliable energy supply for construction projects. This hybrid approach ensures that energy-intensive construction activities have a steady supply of clean energy, reducing dependency on fossil fuels and enhancing overall energy efficiency (Zeng, Lee and Lo, 2020).

Besides, drones contribute to energy efficiency by facilitating the inspection and maintenance of renewable energy installations such as solar panels and wind turbines. By providing rapid and detailed assessments, drones ensure these installations operate at peak efficiency, thereby maximizing their sustainability benefits (Zeng, Lee and Lo, 2020).

Moreover, smart PPE integrated with technologies can help safety officers enhance on-site safety by reducing the occurrence of accidents. The integration of smart PPE with construction management systems allows for the collection and analysis of large amounts of data. This data can be used to maximize workflows, improve resource allocation, and predict maintenance needs, leading to more efficient operations. For instance, wearable devices that track workers' movements and physical exertion can help identify inefficiencies and suggest ergonomic improvements, reducing worker fatigue and improving productivity (Opoku and Lee, 2022) . Thus, smart PPE technologies can improve overall efficiency while mitigating the negligence of the on-site safety workers.

Apart from that, the Internet of Things (IoT) and data analytics also play vital roles in smart building technologies. It enables predictive maintenance and efficient resource management. IoT devices collect extensive data on building operations to detect inefficiencies and predict maintenance needs. This proactive approach helps minimize equipment downtime, extends the lifespan of building components, and reduces the use of resources. Predictive maintenance can prevent equipment failures before they occur, reducing waste and promoting more sustainable operations (Li *et al.*, 2022).

Also, the use of smart grids that enable real-time monitoring and management of energy use could lead to significant improvements in energy efficiency. This is crucial in construction, where energy consumption can be high due to the use of heavy machinery and the need for climate control in buildings. Smart grids can optimize energy use by dynamically adjusting power distribution based on demand, thus reducing wastage (Alotaibi *et al.*, 2020).

Meanwhile, digital twins present the same function as smart grids by integrating various building systems such as HVAC, lighting and electrical systems. Through continuous data collection and analysis, digital twins can identify inefficiencies and suggest useful strategies. For instance, they can adjust heating and cooling settings based on occupancy patterns and weather forecasts, leading to significant energy savings. A study by Lu et al. (2020) highlighted that the implementation of digital twins in building management resulted in a 15-25% reduction in energy consumption through more efficient operations and maintenance practices.

2.5.4 Reduction in Construction Timelines

The speed and efficiency of prefabricated construction also contribute to sustainability. Projects that utilize prefabrication can be completed much faster than those using conventional methods, which reduces the duration of construction-related disturbances and the associated environmental impacts, such as emissions from machinery and transportation (Lešnik *et al.*, 2020).

Furthermore, 3D printing in construction can significantly reduce the time required to complete building projects. The speed and precision of 3D printers can shorten construction timelines, reducing labour costs and decreasing energy use on-site. This rapid construction process not only enhances efficiency but also minimizes the overall environmental impact associated with prolonged construction activities (Li *et al.*, 2022).

2.5.5 Resource Efficiency

Smart building technologies contribute to water conservation efforts. Advanced water management systems monitor and control water usage in real-time, identifying leakages and minimising water consumption for landscaping, sanitation, and other purposes. These systems can thoroughly reduce water waste and offer sustainable water use practices in buildings (Opoku and Lee, 2022).

On the other hand, hybrid renewable energy systems combine a variety of renewable energy sources, such as solar, wind, and biomass, to ensure a reliable and efficient energy supply. These systems enhance resource efficiency by optimizing the use of available renewable resources and reducing dependency on fossil fuels. By integrating different energy sources, hybrid systems can ensure a more consistent energy supply, even when one source is intermittent such as solar power at night or during cloudy days. Additionally, using advanced energy storage solutions such as batteries allows for storing and using excessive energy when needed, further improving efficiency and reducing waste (Lund *et al.*, 2017).

Water-efficient technologies, such as low-flow fixtures, greywater recycling systems, and smart irrigation, play an important role in enhancing resource efficiency in buildings. These technologies reduce water consumption by optimizing usage and recycling water where possible. For example, greywater systems reuse water from sinks and showers to flush toilets which significantly reduces the demand for fresh water. Smart irrigation systems adjust watering schedules based on weather conditions and soil moisture levels, making sure that plants receive the necessary water without wastage (Gleick, 2014). Implementing these technologies in buildings and landscapes leads to substantial water savings and supports sustainable resource management.

Moreover, 3D printing allows for the use of sustainable and recycled materials. Researchers have been exploring the use of materials such as recycled plastics and concrete composites, which not only lower the demand for new raw materials but also divert waste from landfills. This unique technique coincides with the concepts of a circular economy, encouraging the reuse and recycling of resources within the building sector (Dias *et al.*, 2016).

2.5.6 Enhanced Energy Resilience

The integration of green hydrogen into the construction sector can promote energy security and stability. Hydrogen can be stored and transported more easily than some renewable energy sources, such as solar or wind power, which are intermitted and location dependent. This ability to store energy allows for a more reliable energy supply for construction projects, particularly in remote or off-grid locations (Reddy *et al.*, 2023).

Moreover, smart grids are invented to improve the reliability and resilience of the power supply by quickly detecting and responding to faults or disruptions. This is particularly beneficial for construction sites, which can face significant delays and increased costs due to power outages. The ability of smart grids to maintain a stable and uninterrupted power supply ensures smoother operations and reduced downtime (Alotaibi *et al.*, 2020).

Another technology to enhance energy reliability and resilience is hybrid renewable energy systems. By integrating various renewable energy sources, HRES can provide a continuous and stable energy supply, even when one source is intermittent or unavailable. For instance, solar panels can generate electricity during the day, while wind turbines can complement this generation during the night or cloudy periods, ensuring a consistent energy supply. Additionally, energy storage systems like batteries can store excess energy produced during peak generation times to be used during periods of low generation. This ensures a stable power supply and minimizes downtime, which is crucial for maintaining productivity on construction sites (Rezzouk and Mellit, 2015).

2.5.7 Carbon Footprint Reduction

CCS technology can help to enhance the sustainability of construction materials. Incorporating captured CO2 into the production of materials like concrete can create carbon-neutral or even carbon-negative building materials. This process not only decreases the carbon footprint of the materials themselves but also contributes to the overall sustainability of the construction industry. Studies have shown that using CO2-cured concrete can improve its strength and durability while significantly lowering its environmental impact as well as helping construction companies comply with the strict environmental regulations and standards on reducing carbon emissions. By adopting CCS technology, companies can meet the requirements of international agreements and national policies on carbon reduction, thereby avoiding penalties and enhancing their reputation as environmentally responsible entities (Al-Jayyousi *et al.*, 2023).

In addition, drones equipped with advanced imaging and sensing technologies provide high-resolution aerial imagery and real-time data, significantly improving site monitoring and management. This capability allows for precise surveying and mapping, reducing the need for manual site inspections and thereby lowering the carbon footprint associated with transportation and labour. According to Zeng, Lee and Lo (2020), drones used for delivering small equipment and materials across construction sites can significantly reduce the reliance on fuel-consuming vehicles, contributing to lower greenhouse gas emissions.

Besides, smart PPE can also play a crucial role in environmental monitoring. Sensors embedded in the equipment can measure air quality, noise levels, and other environmental parameters on construction sites. This information is valuable for ensuring compliance with environmental regulations and for taking proactive measures to mitigate negative impacts. For example, detecting high levels of dust or pollutants can prompt the implementation of dust suppression techniques or the use of cleaner construction methods (Lin and Chen, 2024). By actively monitoring and managing environmental factors, smart PPE helps to reduce the ecological footprint of construction activities.

By improving energy efficiency and facilitating the use of renewable energy, smart grids significantly reduce greenhouse gas emissions. This aligns with global environmental initiatives and regulatory requirements aimed at mitigating climate change. In the construction industry, where emissions from energy use can be substantial, smart grids help in adhering to stricter environmental standards and achieving sustainability goals (Alotaibi *et al.*, 2020).

By reducing water consumption and promoting efficient water use, water-efficient technologies help to minimize the environmental impact of construction activities. Lower water demand decreases the energy required for water treatment and distribution, thereby reducing the carbon footprint associated with water use (Gleick, 2014).

One of the most significant opportunities presented by hydrogen technology is the reduction of carbon emissions in the construction sector. Hydrogen is used as a clean fuel for construction machinery and equipment, replacing diesel and other fossil fuels that are traditionally used on construction sites. The combustion of hydrogen produces only water vapour as a byproduct, thus eliminating greenhouse gas emissions. According to Hosseini and Wahid (2016), transitioning to hydrogen-fuelled construction equipment could significantly reduce the industry's overall carbon footprint, contributing to global climate change mitigation efforts.

Furthermore, hybrid renewable energy systems significantly reduce carbon emissions and the environmental impact of construction activities. By replacing diesel generators and other fossil fuel-based energy sources with renewable energy, HRES can drastically cut greenhouse gas emissions. For instance, Khan (2021) demonstrated that integrating solar and wind energy systems can reduce CO2 emissions by up to 80% compared to conventional energy systems. This reduction is crucial for the construction industry, which is a significant contributor to global carbon emissions. The shift towards HRES not only benefits the environment but also aligns with regulatory and market pressures to reduce carbon footprints and promote sustainable practices (Khan, 2021).

2.5.8 Improved Safety

Improving safety on construction sites is another critical aspect of sustainability. Drones can determine hazardous or hard-to-reach areas by conducting inspections and surveys without putting workers at risk. This capability not only protects human health and safety but also minimizes the disruption and potential environmental damage caused by accidents. By reducing the need for scaffolding and other temporary structures for inspection purposes, drones also help in cutting down the material usage and waste (Zhu et al., 2022).

Furthermore, robotics and automation enhance worker safety and mitigate the incidence of accidents on construction sites. By automating dangerous tasks, the risk to human workers is minimized, leading to fewer interruptions and delays caused by workplace accidents. This safer working environment can indirectly contribute to sustainability by ensuring continuous workflow and reducing the need for rework due to accidents (Rebai *et al.*, 2024). Also, smart PPE as well as mobile devices which are the wearable devices that can detect hazardous gases or extreme temperatures, alert workers and supervisors to take immediate action, thus preventing potential incidents and ensuring a safer work environment (Opoku and Lee, 2022; Mavi et al., 2021).

2.5.9 Cost Savings and Economic Benefits

The efficiency and reliability provided by smart grids translate to cost savings for construction projects. By optimizing energy use and reducing reliance on fossil fuels, operational costs are lowered. Additionally, the use of energy storage systems can further reduce costs by storing cheaper off-peak electricity for use during peak times, thus balancing the energy load more economically (Alotaibi *et al.*, 2020).

Apart from that, the initial investment in hybrid renewable energy systems can be high, the long-term cost savings and economic benefits are substantial. By reducing reliance on fossil fuels and decreasing energy costs, HRES can lead to significant financial savings for construction projects. The use of renewable energy sources which have low operating and maintenance costs contributes to the overall cost-effectiveness of construction projects. Furthermore, the adoption of HRES can create new job opportunities in the renewable energy sector, from the manufacturing of components to the installation and maintenance of systems, boosting local economies and fostering sustainable economic growth (Rezzouk and Mellit, 2015).

According to Bui et al. (2018), the adoption of CCS technology in the construction industry can lead to significant economic benefits and job creation. The development, installation, and maintenance of CCS facilities require a skilled workforce, which can create new job opportunities in various sectors, including engineering, manufacturing, and project management. Furthermore, the implementation of CCS ensures cost savings in the long run by avoiding potential carbon taxes and penalties associated with high CO2 emissions. These economic benefits can drive investment in CCS technology, fostering innovation and further reducing costs (Bui *et al.*, 2018).

2.5.10 Supporting Circular Economy Principles

The utilization of digital twins supports the principles of a circular economy by enabling the tracking and management of materials throughout their lifecycle. Digital twins can provide a detailed record of the materials used in construction, including their sources, quantities, and recycling potential. This information is crucial for facilitating the reuse and recycling of materials at the end of a building's life, thereby reducing waste and conserving natural resources. For example, a digital twin can be used to create a "material passport" that documents the properties and conditions of materials, making it easier to deconstruct buildings and reclaim valuable resources (Boje et al., 2020).

The integration of CCS technology in the construction industry supports the transition to a circular economy, where waste is minimized while resources are reused. By capturing CO2 emissions, CCS can facilitate the recycling and reuse of CO2 in different industrial processes, such as enhanced oil recovery and the production of synthetic fuels and chemicals (Mac Dowell *et al.*, 2017). This reduces the environmental impact of construction activities meanwhile creating new revenue streams and enhancing resource efficiency.

2.5.11 Summary of the Types of Emerging Technologies and the Opportunities of Emerging Technologies to Create Sustainability

The following Table 2.2 present the summary of the types and opportunities of emerging technologies sorted out from the literature review.

Table 2.2: Literature Maps for Opportunities of Emerging Technologies in Creating Sustainable Construction Industry

Ref	Opportunities / Smart Technologies	Enhanced collaboration & efficiency	Reduction of material waste	Improved energy efficiency	Reduction in construction timelines	Resource efficiency	Enhanced energy resilience	Carbon footprint reduction	Improved safety	Cost savings & economic benefits	Supporting circular economy principles	References
1	BIM	✓		✓								Lu, Won and Cheng (2016), Mavi et al. (2021), Li et al. (2022)
2	3D printing			✓	✓	✓						Buswell et al. (2018), (Dias *et al.*, 2016), Rahmawati et al. (2022), Li et al. (2022)
3	Prefabrication		✓	✓	✓							Pittau et al. (2017), Loizou et al. (2021), Lešnik et al. (2020), Li et al. (2019)
4	Robotics and automation		✓	✓					✓			Bock (2015), Zhu et al. (2022), Ramli, Azizi and Thurairajah (2024), Rebai et al. (2024)
5	Smart building technologies			✓		✓						Li et al. (2022), Opoku and Lee (2022)
6	Drones	✓	✓	✓				✓	✓			Zhu et al. (2022), Zeng, Lee and Lo (2020), Opoku and Lee (2022),
7	PPE technology			✓				✓	✓			Opoku and Lee (2022), Lin and Chen (2024), Mavi et al. (2021),
8	Hydrogen technology						✓	✓				Reddy et al. (2023), Hosseini and Wahid (2016),
9	Mobile & cloud technology	✓							✓			Opoku and Lee (2022), Mavi et al. (2021)

Table 2.2: Literature Maps for Opportunities of Emerging Technologies in Creating Sustainable Construction Industry (Cont'd)

Ref	Opportunities / Smart Technologies	Enhanced collaboration & efficiency	Reduction of material waste	Improved energy efficiency	Reduction in construction timelines	Resource efficiency	Enhanced energy resilience	Carbon footprint reduction	Improved safety	Cost savings & economic benefits	Supporting circular economy principles	References
10	Smart grids & energy storage			✓			✓	✓		✓		Alotaibi et al. (2020), Opoku and Lee (2022),
11	Digital twins	✓		✓							✓	Fuller et al. (2020), Lu et al. (2020), Boje et al. (2020)
12	Water-efficient technologies					✓		✓				Gleick (2014), Ben Jebli, Ben Youssef and Apergis (2019)
13	Hybrid renewable energy system (HRES)					✓	✓	✓		✓		Lund et al. (2017), Rezzouk and Mellit (2015), (Khan, 2021)
14	CCS technology			✓				✓		✓	✓	Zeng, Lee and Lo (2020), Al-Jayyousi et al. (2023), Bui et al. (2018), Mac Dowell et al. (2017)

2.6 Drivers of Emerging Technologies on Sustainability

2.6.1 Regulatory and Market Influences

2.6.1.1 Green Certifications and Standards

Green certifications and standards such as LEED (Leadership in Energy and Environmental Design) and BREEAM (Building Research Establishment Environmental Assessment Method) set benchmarks for sustainability and energy efficiency that encourage companies to integrate advanced technologies into their projects. They incentivize construction companies to incorporate innovative technologies and practices to meet stringent criteria, thus promoting sustainability in the industry (Liu, Chen and Chou, 2019; Mohammed, Hayder and Thiruchelvam, 2023).

One significant impact of green certifications is the promotion of energy-efficient technologies. For example, achieving a high rating in a certification system often requires the incorporation of advanced HVAC systems, high-performance building envelopes, and renewable energy sources such as solar panels. These technologies reduce the carbon footprint of buildings and decrease running costs over time, in line with sustainability goals and regulatory requirements (Plakantonaki *et al.*, 2023). Besides, compliance with green certifications often necessitates the adoption of smart building technologies. These include Internet of Things (IoT) systems for monitoring and optimizing energy use, water management systems to reduce consumption, and advanced waste management solutions. By leveraging big data and real-time monitoring, these technologies ensure that buildings operate at peak efficiency and sustainability, meeting the stringent criteria set by green certification programs (Plakantonaki *et al.*, 2023).

Furthermore, green certifications stimulate innovation in building materials. Standards such as Cradle to Cradle and the Living Building Challenge encourage the use of non-toxic, recyclable, and green materials. This has fostered the development and use of materials like cross-laminated timber, recycled steel, and low-VOC (volatile organic compounds) paints. The adoption of these materials; nevertheless, improves the environmental impact of construction projects but also enhances the health and well-being of occupants by reducing exposure to harmful chemicals (Gholami, Lee and Ali, 2023).

2.6.1.2 Regulatory Requirements

Regulatory frameworks play a vital function in encouraging sustainable construction practices by offering a combination of benefits and penalties. Governments tend to provide financial incentives such as tax rebates, grants, and subsidies for projects that achieve specific sustainability certifications like LEED (Leadership in Energy and Environmental Design) or BREEAM (Building Research Establishment Environmental Assessment Method). For example, tax incentives can substantially alleviate the initial costs of integrating green technologies, making projects that incorporate sustainable materials and energy-efficient systems more financially feasible. Other government subsidies for renewable energy projects can make the incorporation of solar panels, wind turbines, and other green technologies more financially viable for construction companies (Ramli, Azizi and Thurairajah, 2024). Grants and subsidies can further reduce the financial burden, encouraging more companies to pursue sustainable construction practices. These incentives are crucial for the broad adoption of green technologies in the construction industry, driving innovation and ensuring that sustainable practices are integrated into new building projects. Conversely, penalties for non-compliance with environmental regulations serve as a deterrent against unsustainable practices. These penalties can include fines, restrictions, or even the revocation of building permits for projects that fail to meet environmental standards. Such measures ensure that companies adhere to sustainability requirements, further pushing the industry towards adopting green technologies and sustainable practices (Yu et al., 2018; Al-Otaibi et al., 2022).

Furthermore, regulations promoting low-carbon technologies and energy efficiency in construction have led to the increased adoption of smart building technologies. These technologies include advanced HVAC systems, energy management systems, and renewable energy integration, which help buildings comply with regulatory energy performance standards. Such smart systems not only promote the energy efficiency of buildings but contribute to reducing operational costs and enhancing overall sustainability. The integration of these advanced technologies aligns with various international green certification standards, which further push the construction industry towards sustainable practices. By adopting innovative technologies like 3D printing for sustainable materials, prefabrication to minimize waste, and robotics for precision in construction, the industry can better comply with these stringent standards and achieve significant improvements in sustainability (W. Chen *et al.*, 2023).

2.6.1.3 Market Demand

Market demand influences the adoption of innovative technologies such as Building Information Modelling (BIM), which enhances efficiency and sustainability in construction projects. According to Salzano et al. (2024), BIM plays a significant factor in maximizing resource utilization, minimizing waste, and improving the overall environmental performance of construction projects while IoT devices monitor the usage of energy and environmental conditions in real-time, enabling adaptive management of building systems to enhance renewable energy and the comfort of the users. This technology adoption is largely driven by the need to meet expectations for sustainable building solutions that are both cost-effective and environmentally friendly.

Furthermore, the push for sustainable construction is supported by the increasing market value of green technologies. The integration of technologies such as smart building systems, energy-efficient materials, and renewable energy sources is becoming more prevalent as market demand grows. The trend towards sustainable technology innovation is evident in the construction industry, driven by market demands and the need for sustainable development while the need for green buildings is fostered by a combination of environmental consciousness and the economic benefits associated with reduced operational costs and improved building performance (Zhang, Ma and Liu, 2020).

2.6.1.4 Public and Stakeholder Pressure

Stakeholder pressure often results in companies adopting more sustainable practices to meet the expectations of consumers and advocacy groups. For instance, stakeholder groups can exert influence through campaigns and boycotts, which not only create reputational risks for companies but also provide valuable knowledge and insights into sustainability issues (Siems, Seuring and Schilling, 2023). Such external pressures compel companies to innovate and integrate sustainable technologies to maintain their market position and avoid negative publicity. In addition to external pressures, internal stakeholders such as employees and investors are increasingly advocating for sustainable practices. Engaging with stakeholders to understand their concerns can lead to proactive sustainability measures, which in turn foster innovation and improve overall sustainability performance (Siems, Seuring and Schilling, 2023).

Apart from that, public pressure has been instrumental in driving regulatory changes that mandate the use of greener technologies. For example, the energy transition in Germany, largely influenced by public and political pressure, has led to significant advancements in renewable energy technologies and sustainable energy practices (Kappner, Letmathe and Weidinger, 2023). This transition underscores how stakeholder expectations can lead to policy reforms that promote the adoption of sustainable technologies in various industries, including construction. The commitment to global sustainability initiatives, such as the United Nations' Agenda 2030, further amplifies the role of stakeholder pressure in promoting sustainable practices. The agenda emphasizes the importance of public, industrial, and societal collaboration in achieving the Sustainable Development Goals (SDGs) (González-Sánchez, Alonso-Muñoz and Medina-Salgado, 2023). This collective effort underscores the critical role of public and stakeholder pressure in steering industries, including construction, towards the adoption of sustainable technologies and practices.

2.6.1.5 Global Environmental Initiatives

Global environmental initiatives often come with financial mechanisms and benefits to support the adoption of sustainable technologies. The Green Climate Fund and other similar initiatives provide funding and technical support to projects that align with climate goals, encouraging the construction industry to innovate and integrate sustainable practices. This support helps offset the initial costs associated with adopting new technologies, making it more feasible for companies to transition towards greener practices (Geng, 2021).

Moreover, initiatives such as the United Nations' Sustainable Development Goals (SDGs) promote the adoption of smart building technologies and sustainable practices. These goals emphasize sustainable cities and neighbourhoods, low-cost and clean energy, and industrial innovation and infrastructure. The construction industry responds by leveraging technologies such as Building Information Modelling (BIM), Internet of Things (IoT) devices, and energy management systems to enhance building efficiency and sustainability. These initiatives drive regulatory frameworks at national and regional levels, setting the stage for stricter environmental regulations and standards. This regulatory pressure pushes the construction industry to innovate continuously, ensuring compliance while simultaneously promoting sustainability. Emerging technologies like the Internet of Things (IoT) and smart building systems are increasingly utilized to monitor and maximize energy consumption and resource allocation, aligning construction practices with global sustainability goals (T. Chen *et al.*, 2023).

2.6.1.6 Carbon Pricing and Emissions Trading System (ETS)

The construction industry is energy-intensive, with significant carbon emissions resulting from building materials production, transportation, and on-site construction activities. The price of carbon raises the cost of power generated from fossil fuels, incentivizing the industry to adopt energy-efficient practices and technologies. By reducing energy consumption, companies can lower their operating costs and their carbon liabilities, making sustainability a financially attractive option (Lilliestam, Patt and Bersalli, 2021).

Besides, the ETS can drive the demand for low-carbon building materials. As companies seek to minimize their carbon footprints, there is an increased demand for materials like recycled steel, low-carbon concrete, and sustainable timber. This shift not only reduces emissions but also fosters innovation in material science and manufacturing processes, leading to a better sustainable construction industry (Joltreau and Sommerfeld, 2019).

Furthermore, carbon pricing and ETS stimulate the development and utilization of low-carbon technologies. The potential for financial gain from selling emissions allowances motivates companies to invest in innovative solutions such as HVAC systems, renewable energy integration, and advanced construction techniques that minimize waste and emissions. This continuous drive for innovation not simply reduces the ecological impact of construction activities while further leads to long-term cost savings and operational efficiencies (Xu, 2021).

2.6.2 Corporate and Organizational Factors

2.6.2.1 Corporate Social Responsibility (CSR)

Corporate Social Responsibility (CSR) initiatives motivate companies to integrate advanced technologies that only enhance their environmental performance but also address social and economic challenges. CSR drives the adoption of technologies that reduce the environmental footprint of construction activities. For instance, digitalization and the use of Building Information Modeling (BIM) have become prevalent given their potential to improve resource efficiency and reduce waste. BIM facilitates better planning and management of construction projects, leading to more sustainable outcomes by minimizing material use and enhancing energy efficiency (Zhong and Ren, 2024).

CSR initiatives often emphasize the importance of worker safety and community well-being. Technologies such as wearable devices and drones enhance on-site safety by monitoring ecological conditions and providing real-time data to prevent accidents. Furthermore, CSR-driven projects frequently incorporate smart building technologies that improve the living conditions of communities by ensuring buildings are energy-efficient, comfortable, and healthy (Deng *et al.*, 2020). These technologies not only fulfil CSR goals but also foster the overall quality of life for occupants and workers.

From an economic perspective, CSR encourages the use of technologies that enhance operational efficiency and reduce costs in the long term. The adoption of green construction practices, supported by CSR, leads to lower operational costs due to energy savings and reduced waste management expenses. Companies that invest in CSR-driven technological innovations often experience increased market competitiveness and improved stakeholder relationships, as they are seen as leaders in sustainability (Dimakopoulou *et al.*, 2023).

Besides, CSR also drives compliance with environmental regulations and standards, which often necessitate the adoption of new technologies. For example, the push for reducing carbon emissions has led to the development and implementation of carbon capture and storage (CCS) technologies in the construction industry. These technologies in line with CSR goals by mitigating climate impact and ensuring compliance with stringent environmental policies (Du *et al.*, 2024).

2.6.2.2 Risk Management

An effective risk management necessitates the use of technologies that can predict and manage potential risks more accurately. For instance, Building Information Modeling (BIM) is frequently used to simulate and visualize construction projects, identifying potential issues before they occur and facilitating better planning and resource management. This not only reduces waste but also make sure that projects are completed within time frame and budget, aligning with sustainability goals (Chen *et al.*, 2022).

Moreover, the adoption of emerging technologies such as drones, Internet of Things (IoT), and Geographic Information Systems (GIS) in risk management practices allows for monitoring in real-time and collecting data. These technologies enhance the ability to detect risks early and respond promptly, thereby improving the overall safety and sustainability of construction projects. For example, drones can be used for site inspections, reducing the need for labour and minimizing the possibility of accidents (Xu *et al.*, 2023).

Risk management also drives the use of technologies that enhance the sustainability of construction practices by promoting the efficient use of resources and minimizing environmental impact. Technologies like prefabrication and modular construction are adopted to mitigate risks associated with traditional on-site construction, such as delays due to weather conditions and on-site waste generation. These methods are more controlled and produce less waste, contributing to more sustainable construction practices (Chen *et al.*, 2022).

2.6.2.3 Client and Investor Expectations

Clients today are increasingly aware of the environmental issues surrounding construction projects and demand sustainable practices. This shift has driven the integration of technologies such as Building Information Modeling (BIM) and advanced analytics. BIM facilitates better planning, resource management, and waste reduction, aligning with clients' sustainability goals (Chen *et al.*, 2022). Clients also expect faster project delivery and higher quality, prompting prefabrication and modular construction methods, which are more efficient and produce less waste than traditional methods (Xu *et al.*, 2023).

Investors, particularly those focused on environmental, social, and governance (ESG) criteria, prioritize funding for projects demonstrating a sustainability commitment. This trend has led to significant investment in construction technologies that improve energy efficiency, reduce emissions, and enhance overall project sustainability. Technologies such as AI and IoT are heavily funded as they provide real-time data and insights that improve decision-making, operational efficiency, and compliance with environmental regulations (Xu *et al.*, 2023).

2.6.2.4 Reduction of Operational Costs

Emerging technologies such as Building Information Modeling (BIM), the Internet of Things (IoT), and Artificial Intelligence (AI) are pivotal in reducing operational costs. BIM, for instance, enhances collaboration better collaboration among stakeholders, resulting in fewer mistakes and rework throughout the construction process. This technology allows for detailed visualization and simulation of projects, helping to identify potential issues before they arise on-site, thus reducing delays and associated costs (Chen *et al.*, 2022).

Besides, the use of data-driven modelling and analytics also plays a crucial role in operational cost reduction. By leveraging large datasets and advanced analytics, construction companies can optimize project schedules, predict maintenance needs, and enhance decision-making processes. This predictive capability reduces downtime and increases the lifespan of buildings, resulting in long-term savings (Ma *et al.*, 2023).

Moreover, the synergy between different emerging technologies can amplify cost savings. For example, combining BIM with AI and machine learning can automate routine tasks such as scheduling and resource management, leading to more efficient project management and significant cost reductions. This integrated approach improves operational efficiency while supporting dynamic and responsive project execution that is in line with the principles of sustainable construction (Chen *et al.*, 2022).

2.6.3 Technological and Innovation Approach

2.6.3.1 Technological Advancements

Technological advancements, such as Building Information Modeling (BIM), the Internet of Things (IoT), and Artificial Intelligence (AI), significantly enhance project efficiency and reduce costs. BIM supports for detailed 3D modeling, which helps stakeholders plan and coordinate more effectively. This reduces mistakes and rework, leading to cost savings and timely project completion (Chen *et al.*, 2022). IoT devices enable real-time monitoring of construction sites, optimizing resource use and minimizing waste. AI applications in predictive analytics help in forecasting project risks and maintenance needs, further cutting down operational costs and improving overall project management (Ma *et al.*, 2023).

The continuous development of digital tools and platforms fosters innovation in the construction industry. Integrated platforms that combine various technologies, such as BIM with Geographic Information Systems (GIS) and Light Detection and Ranging (LiDAR), enhance project visualization and data accuracy. These integrations enable comprehensive project management, from design and planning to execution and maintenance, ensuring that sustainability is embedded throughout the project lifecycle (Chen *et al.*, 2022).

2.6.3.2 Innovation in Materials Science

Recent advancements in materials science have focused on creating sustainable substitutes for traditional construction materials. For instance, the use of geopolymer composites made from industrial and agricultural waste materials presents a significant step towards reducing the ecological impact of construction. These materials, which include aluminosilicates, provide a lower carbon footprint compared to conventional Portland cement, while also providing superior durability and resistance to chemical degradation (Ferrara, La Noce and Sciuto, 2023). This innovation not only reduces the reliance on non-renewable resources but also mitigates the environmental issues regarding waste disposal.

Besides, the improvement of new materials produced in construction is their enhanced durability. Traditional materials like concrete and steel, while robust often succumb to wear and degradation over time. Innovations such as ultra-high-performance concrete (UHPC) and self-healing materials offer superior strength and longevity by reducing frequent repairs and replacements. This durability not only protect resources but also minimizes the environmental impact regarding the production and transportation of construction materials (De Belie *et al.*, 2018).

2.6.3.3 Technological Integration and Smart Systems

BIM, in combination with AI, has become a cornerstone in modern construction for improving accuracy and efficiency. These technologies enable precise modeling and simulation of construction projects, allowing for early detection and correction of design errors, thereby reducing material waste and rework. According to Jalaei, Jrade and Nassiri (2015), integrating BIM with decision support systems helps in selecting sustainable building components, optimizing resource utilization and minimizing environmental impact. This integration ensures that projects are executed with greater precision, aligning with sustainability goals (Ghazal and Hammad, 2023).

IoT and smart sensors are instrumental in real-time monitoring of construction activities and building performance. These technologies facilitate the collection of large amounts of data, which can be analysed to predict maintenance needs and prevent failures. For example, the use of smart sensors to monitor structural health can help in timely maintenance, thus extending the lifespan of buildings and decrease the need for new development, which aligns with sustainable practices (Ghazal and Hammad, 2023). Pan et al. (2018) highlighted that automation and robotics in construction, supported by IoT, can significantly enhance sustainability by improving energy efficiency and reducing labour costs.

Smart systems also contribute to effective energy management in buildings. Technologies such as smart grids and energy management systems enable the optimization of energy use by adjusting consumption based on real-time data. This not only reduces operational costs but also minimizes the carbon footprint of buildings. The adoption of these systems ensures that energy is used efficiently, promoting sustainable construction practices (Ghazal and Hammad, 2023). Mytafides, Dimoudi and Zoras (2017) demonstrated that transforming buildings into zero-energy entities through smart energy management can significantly reduce environmental impact.

AI and machine learning algorithms act as a critical factor in facilitating sustainable decision-making in construction projects. These technologies can analyse historical data and predict future trends, assisting project managers in making informed decisions that favour sustainability. For instance, AI can optimize construction schedules and supply chains to minimize delays and lower carbon dioxide regarding transportation and logistics (Ghazal and Hammad, 2023). (Alireza *et al.*, 2017) emphasized that BIM-enabled sustainability assessments aid in making informed material supply decisions, which are crucial for sustainable construction.

2.6.4 Resource and Environmental Considerations

2.6.4.1 Resource Scarcity

The scarcity of resources forces construction companies to optimize their use of available materials. This includes reducing waste through precise planning and efficient design, as well as implementing practices like modular construction, which minimizes material use and waste. Efficient resource utilization not only conserves scarce resources but also reduces costs, making sustainability economically advantageous for construction firms (Mellado and Lou, 2020).

As resources become scarcer, the construction industry increasingly turns to recycling and reusing materials. This involves repurposing construction waste such as concrete, steel, and timber, thereby reducing the need for virgin materials. Advanced recycling technologies and circular economy principles are being integrated into construction practices to create a better sustainable lifecycle for building materials. By enabling these practices, the industry can significantly lower its environmental impact and reduce the depletion of natural resources (Opoku, Agyekum and Ayarkwa, 2022).

2.6.4.2 Energy Efficiency Goals

One of the primary ways to drive energy efficiency goals is through emerging technologies, such as Building Information Modelling (BIM), smart building systems, and renewable energy integrations, which play a crucial function in achieving energy efficiency goals. BIM allows for precise planning and optimization of energy use throughout the building's lifecycle, from design to demolition. Smart building systems, equipped with sensors and automation, optimize energy usage through real-time data to adjust lighting, heating, and cooling systems based on occupancy patterns (Sanderson, 2022).

Furthermore, technological advancements in renewable energy integration are also propelled by energy efficiency goals. For instance, the adoption of photovoltaic (PV) systems and solar thermal collectors into building designs is becoming increasingly common. These technologies not only help in achieving energy efficiency targets but also reduce the dependency on non-renewable energy sources. Research indicates that PV systems on rooftops can significantly cut down operational costs and improve environmental performance, contributing to the sustainability of buildings (Abdul-Majeed and Al-Riyami, 2019).

Environmentally, energy-efficient buildings can lead to a reduction of greenhouse gases and the conservation of natural resources. By minimizing energy use, these buildings help decrease the impacts of climate change and improve sustainable development. The adoption of renewable energy sources further enhances their environmental performance, making them key components in the transition towards a sustainable construction industry (Sanderson, 2022; Chen et al., 2024).

2.6.4.3 Environmental Awareness

The circular economy is driven by environmental awareness and promotes using sustainable materials and waste-reduction technologies. The construction industry is increasingly adopting materials that are recyclable and have a lower environmental impact. Innovations in materials science, such as the development of sustainable concrete and biodegradable composites, are reducing the environmental footprint of construction projects (Gu *et al.*, 2023). Additionally, technologies that facilitate the reuse and recycling of construction waste are being implemented to minimize landfill use and resource depletion.

In addition, real-world applications of these technologies illustrate the effectiveness of environmental awareness in driving sustainable construction.

For example, in Australia, the integration of sustainability concepts in higher education has enhanced the competencies of construction professionals, leading to more effective implementation of sustainable practices in infrastructure projects (Sandanayake, Bouras and Vrcelj, 2022). Similarly, various global projects have demonstrated the benefits of incorporating renewable energy systems and sustainable materials, highlighting the tangible impacts of these technologies on reducing environmental degradation.

2.6.4.4 Urbanization and Sustainable City Planning

Sustainable city planning involves creating city spaces which are not only functional and efficient but also environmentally friendly and socially inclusive. Advanced technologies act as an important tool in this context by providing tools for better planning and decision-making. Geographic Information Systems (GIS) and Building Information Modeling (BIM) allow planners to visualize and analyze urban spaces comprehensively, leading to more informed decisions about land use, transportation networks, and green spaces. These tools enable the simulation of various scenarios, helping planners to identify the most sustainable options (Bordoloi and Acharya, 2023).

The proliferation of data through urban sensors and connected devices has given rise to smart cities that rely on data-driven insights to enhance urban management. Big data analytics can help city planners and managers understand patterns and trends in urban activities, leading to more efficient resource allocation and improved public services. For instance, data collected from smart meters can help optimize energy usage, while data from transportation networks can inform improvements in public transit systems (Bibri and Krogstie, 2019).

Emerging technologies also foster greater collaboration and inclusivity in urban planning. Digital platforms enable broader stakeholder engagement, allowing citizens to participate in planning processes and voice their concerns and preferences. This collaborative approach ensures that city development projects are more in conjunction with the community needs and ambitions, resulting in more sustainable and acceptable outcomes (Bordoloi and Acharya, 2023).

2.6.5 Competitive and Strategic Motivations

2.6.5.1 Competitive Advantage

Firms that adopt innovative technologies can distinguish themselves in a highly competitive market. By implementing sustainable construction practices, companies can meet increasing client and investor demands for eco-friendly solutions, which can attract new business and retain existing clients. For instance, firms using Building Information Modelling (BIM) and other digital technologies can offer improved project efficiency, accuracy, and sustainability, thus appealing to environmentally conscious stakeholders (Chen *et al.*, 2022).

Emerging technologies often lead to significant cost savings by improving operational efficiency. Technologies such as drones for site surveys, AI for predictive maintenance, and advanced project management software help streamline operations, reduce waste, and lower labour costs. These efficiencies not only reduce operational expenses but also enhance project delivery timelines and quality, providing a competitive advantage in bidding for new projects (Liu *et al.*, 2020).

Adopting cutting-edge technologies allows construction firms to innovate continuously, setting themselves apart from competitors. For example, 3D printing in construction can drastically reduce material waste and construction time, offering a unique selling proposition. Firms that leverage such innovations can achieve superior project outcomes and customer satisfaction, thereby gaining a sustainable competitive edge (Chen *et al.*, 2022).

2.6.5.2 Health and Well-being Concerns

Wearable devices and smart sensors such as smart helmets and vests have been adopted to monitor workers' health and safety in real time. These devices can track significant signs, detect hazardous environmental conditions, and alert workers and supervisors to potential dangers. This proactive approach helps prevent accidents and health issues, fostering a safer work environment (Oesterreich and Teuteberg, 2016).

Besides, BIM is used not only for project planning and management but also as a tool for risk prevention and safety planning. By simulating construction processes, BIM can identify potential hazards and enable the development of safer work methods (Tender *et al.*, 2022). Moreover, virtual and augmented reality technologies offer immersive training experiences, helping workers recognize and mitigate potential hazards. VR simulations can replicate dangerous scenarios in a controlled environment, allowing workers to practice safety protocols without risk. Similarly, AR can overlay critical safety information on physical spaces, guiding workers through complex tasks safely and efficiently (Kassem, Benomran and Teizer, 2017). Also, the Internet of Things (IoT) enables the creation of interconnected systems that monitor and manage construction site operations. IoT devices can collect data on equipment performance, environmental conditions, and worker movements, providing insights that enhance safety and efficiency. For example, IoT sensors can detect unsafe levels of dust, noise, or toxic gases, prompting immediate corrective actions to protect workers' health (Chen *et al.*, 2022).

2.6.5.3 Educational and Training Programs

One prominent initiative is the Malaysian Industrial Energy Efficiency Improvement Project (MIEEIP). Launched with support from the United Nations Development Programme (UNDP) and the Global Environment Facility (GEF), this project focuses on enhancing energy efficiency in multiple industrial sectors, including construction. This program helps mitigate carbon-dioxide emissions as well as reduce energy consumption each year by 732,000t and 1074GW accordingly (Mekhilef *et al.*, 2014).

Additionally, the Sustainable Energy Development Authority (SEDA) Malaysia has been proactive in organizing training programs under initiatives like the Government Lead By Example (GLBE) Program and the Sustainable Achieve via Energy Efficiency (SAVE) Program. These programs include modules on energy management in buildings, the application of Malaysian Standards for energy efficiency, and energy auditing. Such training programs are crucial for building a knowledgeable workforce capable of implementing and maintaining energy-efficient practices in construction projects (SEDA, 2017).

2.6.6 Summary of Drivers to Use Emerging Technologies

Table 2.3 demonstrates the summary of drivers to use emerging technologies in the construction industry which is sorted from the literature review.

Table 2.3: Drivers of Emerging Technologies in the Sustainable Construction Industry

Ref		No. of papers	Sources
	Regulatory and Market Influences		
1	Green certifications and standard	4	Liu, Chen and Chou (2019), Mohammed, Hayder and Thiruchelvam (2023), Plakantonaki et al. (2023) Gholami, Lee and Ali (2023)
2	Regulatory requirements	4	Ramli, Azizi and Thurairajah (2024), Yu et al. (2018), Al-Otaibi et al. (2022), W. Chen et al. (2023)
3	Market demand	2	Salzano et al. (2024), Zhang, Ma and Liu (2020)
4	Public and stakeholder pressure	3	Siems, Seuring and Schilling (2023), Kappner, Letmathe and Weidinger (2023), González-Sánchez, Alonso-Muñoz and Medina-Salgado (2023)
5	Global environmental initiatives	2	Geng (2021), T. Chen et al. (2023)
6	Carbon pricing and emissions trading systems (ETS)	3	Lilliestam, Patt and Bersalli (2021), Joltreau and Sommerfeld (2019), Xu (2021)
	Corporate and Organizational Factors		
1	Corporate social responsibility (CSR)	4	Zhong and Ren (2024), Deng et al. (2020), Dimakopoulou et al. (2023), Du et al. (2024)
2	Risk management	2	Chen et al. (2022), Xu et al. (2023)
3	Client and investor expectations	2	Chen et al. (2022), Xu et al. (2023)
4	Reduction of operational costs	2	Chen et al. (2022), Xu et al. (2023)
	Technological and Innovation Drivers		
1	Technological advancements	2	Chen et al. (2022), Ma et al. (2023)
2	Innovation in materials science	2	Ferrara, La Noce and Sciuto (2023), De Belie et al. (2018)
3	Technological integration and smart systems	4	Ghazal and Hammad (2023), Mytafides, Dimoudi and Zoras (2017), Pan et al. (2018), Alireza et al. (2017)

Table 2.3: Drivers of Emerging Technologies in the Sustainable Construction Industry (Cont'd)

Ref		No. of papers	Sources
	Resource and Environmental Considerations		
1	Resource scarcity	2	Mellado and Lou (2020), Opoku, Agyekum and Ayarkwa (2022)
2	Energy efficiency goals	3	Sanderson (2022), Abdul-Majeed and Al-Riyami (2019), Chen et al. (2024)
3	Environmental awareness	2	Gu et al. (2023), Sandanayake, Bouras and Vrcelj (2022)
4	Urbanization and sustainable city planning	2	Bordoloi and Acharya (2023), Bibri and Krogstie (2019)
	Competitive and Strategic Motivations		
1	Competitive advantage	2	Chen et al. (2022), Liu et al. (2020)
2	Health and well-being concerns	4	Oesterreich and Teuteberg (2016), Tender et al. (2022), Kassem, Benomran and Teizer (2017), Chen et al. (2022)
3	Educational and training programs	2	Mekhilef et al. (2014), SEDA (2017)

2.7 Challenges to Adopt Emerging Technologies

2.7.1 High Initial Cost

The high initial costs of implementing smart technologies in the construction industry present significant challenges to achieving sustainability. These technologies, such as Building Information Modeling (BIM) and 3D printing, require substantial upfront investments in new equipment, software, and training, which can be prohibitive for many firms, particularly smaller ones (Kissi, Aigbavboa and Kuoribo, 2023). Furthermore, clients and developers often focus on short-term costs over long-term benefits, making it difficult for construction firms to justify the higher initial costs of sustainable technologies. This short-term focus can lead to a preference for cheaper, less sustainable options, thereby hindering the widespread adoption of green technologies in the industry (D'Alpaos and Bragolusi, 2018).

To address these challenges, it is essential to develop supportive policies and financial incentives which alleviate the initial cost burden. Subsidies, tax incentives, and grants can play a vital function in encouraging the adoption of sustainable technologies. Additionally, promoting awareness of the long-term benefits and potential cost savings in conjunction with sustainable construction practices can help shift the industry's focus from short-term costs to long-term gains (Matarneh and Hamed, 2017).

2.7.2 Limited Case Study and Support

It is crucial to have documented successes and failures to boost the future implementation and adaptations of emerging technologies. However, the scarcity of detailed case studies limits the understanding of how emerging technologies perform under various conditions. Without this evidence, companies may be thoughtful about investing in new technologies as the perceived high risks and unknown outcomes (Chen *et al.*, 2022). Also, it appears that the benefits of emerging technologies are not realized on a broader scale due to insufficient case studies. This will impede the industry's ability to reduce its environmental footprint and achieve sustainability targets (Maqbool, Saiba and Ashfaq, 2023).

Furthermore, a vibrant ecosystem of case studies usually will foster the innovation of emerging technologies by demonstrating diverse applications and encouraging iterative improvements. Nevertheless, innovation stagnates as firms are less likely to experiment with new technologies without a clear understanding of potential outcomes (Zhang *et al.*, 2024).

2.7.3 Lack of Awareness and Knowledge

A primary issue is the limited knowledge concerning the prospective benefits that emerging technologies can bring to sustainable construction. Many construction professionals are not fully informed about how technologies such as Building Information Modeling (BIM), prefabrication, and renewable energy systems can enhance project outcomes and reduce environmental impacts. This lack of awareness leads to a reluctance to invest in and adopt these technologies (Chan *et al.*, 2018). The study highlights that without a clear understanding of the advantages, stakeholders are less likely to support the integration of new technologies into their projects.

Besides, the slow dissemination of information about new advancements in sustainable technologies also hampers their adoption. Innovations in construction technology often originate from research institutions and advanced industry sectors, and it takes time for this knowledge to permeate through to the broader industry. According to (Goh and Loosemore, 2017), they emphasize that the construction industry is often slow to get new information and integrate it into practice due to the fragmented nature of the industry and the lack of effective communication channels. This delay in information flow means that many construction firms remain unaware of the latest sustainable technologies and practices.

Moreover, the construction industry's workforce often lacks the necessary training and education to effectively utilise emerging technologies. This gap in knowledge extends to both technical skills and understanding the broader implications of sustainability. Darko, Zhang and Chan (2017) emphasizes that educational institutions and professional training programs have not kept pace with the rapid development of new technologies. As a result, there is a professional shortage who excel in using advanced tools and methodologies, which hampers the industry’s ability to implement sustainable practices.

2.7.4 Regulatory and Policy Barriers

One of the primary regulatory barriers is the existence of outdated regulations that do not accommodate the latest technological advancements. Many building codes and standards were established before the advent of modern sustainable technologies, such as green building materials, renewable energy systems, and advanced construction methods. These outdated regulations can restrict the use of innovative technologies, as they often do not recognize or approve new materials and methods. Consequently, construction firms may face difficulties in obtaining necessary permits and approvals, leading to delays and additional costs (Darko, Zhang and Chan, 2017a).

Besides, bureaucratic hurdles, such as complex and lengthy approval processes, also pose significant challenges. These hurdles can be particularly costly for small and medium-sized enterprises (SMEs) which may lack the resources to manage complex regulatory landscapes. Bureaucratic inefficiencies can lead to significant delays in project timelines, increased costs, and reduced competitiveness (Poirier, Staub-French and Forgues, 2015). Hence, simplifying and streamlining regulatory processes is essential to encourage the integration of sustainable technologies and practices in the construction industry.

2.7.5 Technological Uncertainty

Firstly, the rapid pace of technological innovation often leads to a lack of stability and predictability. New technologies can emerge quickly, making it difficult for companies to keep up or invest confidently in long-term projects. This scenario is particularly problematic in the construction industry, where projects can span several years. As a result, firms might be hesitant to adopt advanced technologies due to fears of obsolescence or the risk that newer, more efficient solutions may soon become available (Subramaniam and Loganathan, 2022).

Furthermore, the evolving nature of technological standards and regulations adds another layer of complexity. The construction industry is heavily regulated, and the integration of smart technologies must comply with these regulations. Uncertainty around whether emerging technologies will meet future regulatory requirements can deter companies from adopting them. This issue is compounded by the often-high costs associated with implementing new technologies, including training staff and updating infrastructure (Burleson *et al.*, 2023).

2.7.6 Interoperability Issues

A significant aspect of interoperability issues lies in the exchange and compatibility of data between different systems. Emerging technologies such as Building Information Modeling (BIM), Geographic Information Systems (GIS), and Internet of Things (IoT) devices generate large amounts of data that must be integrated and shared across different platforms. According to Zhong et al. (2019), the lack of standardized data formats and procedures can lead to fragmented information flows, data loss, and misinterpretation, which undermine the effectiveness of these technologies. When systems cannot communicate seamlessly, the benefits of these technologies such as improved efficiency and reduced environmental impact are not fully realized (Zhong et al., 2019). As stated by Karan and Irizarry 2015), poor interoperability can hinder the real-time sharing of information and collaboration between project teams, negatively affecting project outcomes and sustainability efforts. At the same time, these barriers can result in duplicate efforts, increased waste and inefficient use of resources.

The integration of new technologies with legacy systems presents another interoperability challenge. Many construction firms still use traditional methods and older software systems incompatible with modern, sustainable technologies. The coexistence of old and new systems can create technical difficulties, such as data transfer issues and synchronisation problems. These issues can delay project timelines and increase the complexity of managing construction processes, thereby impacting the overall sustainability of the project (Poirier, Staub-French and Forgues, 2015).

2.7.7 Infrastructure and Logistics Challenges

The construction industry often struggles with outdated infrastructure that is ill-equipped to support advanced technologies such as Building Information Modeling (BIM), 3D printing and IoT-enabled devices. These technologies require effective digital infrastructure, including high-speed internet and vast data storage capabilities which are often lacking. Besides, traditional infrastructure may not be compatible with the new hardware and software required for these emerging technologies, leading to increased costs and logistical complexities (Milani, Mohr and Sandri, 2021). If the supporting infrastructure is not up to standard, reduced waste cannot be fully utilized due to emerging technologies designed to improve energy efficiency. This resulted in a slower transition to green building practices and delays in achieving sustainability targets set by initiatives like the UN Sustainable Development Goals (SDGs) (Sandanayake, Bouras and Vrcelj, 2022).

Logistics, mainly known as supply chain management, also poses significant barriers. The integration of new technologies necessitates an efficient and responsive supply chain that can handle the increased complexity and coordination required. Sustainable construction relies on the timely and precise delivery of materials and components; however, it is often disrupted by poor logistics. For example, the adoption of modular construction techniques which are touted for sustainability benefits, depends heavily on a well-coordinated supply chain to deliver prefabricated components just-in-time to construction sites. As a result, inefficient logistics might lead to delays, increased cost and material wastage, undermining the sustainability goals of such projects (Sandanayake, Bouras and Vrcelj, 2022).

2.7.8 Complexity of Sustainable Design

Sustainable design demands a comprehensive strategy that takes into account the interconnections between various environmental, social, and economic factors. For instance, achieving sustainability in construction involves using environmentally friendly materials, energy-efficient technologies and renewable energy sources alongside ensuring social equity and economic viability. The intricate coordination required to align these diverse elements often leads to significant challenges, especially when emerging technologies are involved (Zavadskas, Šaparauskas and Antucheviciene, 2018). Also, BIM as well as Generative Design requires high level expertise to optimize design solutions and ensure structural integrity while maintaining the sustainability goals (Cascone, Parisi and Caponetto, 2024). Thus, by addressing these complexities through enhanced training, interdisciplinary collaboration and the development of supportive frameworks, the construction industry can better leverage emerging technologies to achieve its sustainability goals.

2.7.9 Measurement and Verification Issues

Emerging technologies in construction, such as Building Information Modeling (BIM), smart sensors, and automated systems heavily rely on precise measurement and verification processes to ensure that they perform as intended and contribute to sustainability goals. Nevertheless, the integration and implementation of these technologies often face challenges related to the accuracy, reliability, and standardization of Measurement and Verification (M&V) protocols. Without robust M&V systems, it is difficult to validate the performance of new technologies, making stakeholders hesitant to invest in them due to perceived risks and uncertainties (Moshood, Rotimi and Shahzad, 2024).

In addition, the absence of standardized metrics and benchmarks for new technologies is a significant hurdle. Without industry-wide standards, comparing performance data across different projects or technologies becomes challenging. This lack of standardization hampers the ability to validate the effectiveness of sustainable technologies and limits the scalability of successful implementations (Dobrucali *et al.*, 2024).

2.7.10 Limited Availability of Green Materials

The scarcity of green materials hampers the development and application of these technologies. For instance, 3D printing in construction is touted for its potential to reduce waste and enhance precision. However, its environmental benefits are significantly diminished if the materials used are not sustainable. Traditional construction materials like concrete and steel have high carbon footprints, and their use in advanced technologies without green alternatives continues to perpetuate environmental degradation (Buswell *et al.*, 2018).

Moreover, sustainable materials are critical for the implementation of smart building technologies that maximize energy use and improve environmental performance. Traditional construction materials do not adequately support the advanced functionalities required for smart systems, thereby limiting the potential of these technologies to achieve energy efficiency and reduce carbon footprints (Ouf and Issa, 2017). The continued reliance on non-sustainable materials perpetuates these environmental issues, counteracting efforts to make the industry more sustainable. For example, the production of conventional concrete generates approximately 8% of global carbon dioxide emissions. As a result, without the utilization of low-carbon and recycled materials, the construction industry will struggle to meet global sustainability targets and reduce its environmental impact (Habert *et al.*, 2020).

2.7.11 Summary of the Challenges that Influence the Use of Emerging Technologies

The summary of challenges using emerging technologies is presented in Table 2.4 which is abstracted from the literature view.

Table 2.4: Challenges to Adopt Emerging Technologies in the Construction Industry

Ref	Challenges	No. of papers	Sources
1	High initial cost	3	Kissi, Aigbavboa and Kuoribo (2023), D'Alpaos and Bragolusi (2018), Matarneh and Hamed (2017)
2	Limited case study and support	3	Chen et al. (2022), Maqbool, Saiba and Ashfaq (2023), Zhang et al. (2024)
3	Lack of awareness and knowledge	3	Chan et al. (2018), Goh and Loosemore (2017), Darko, Zhang and Chan (2017)
4	Regulatory and policy barriers	2	Darko, Zhang and Chan (2017), Poirier, Staub-French and Forgues (2015)
5	Technological uncertainty	2	Subramaniam and Loganathan (2022), Burleson et al. (2023)
6	Interoperability issues	3	Zhong et al. (2019), Karan and Irizarry (2015), Poirier, Staub-French and Forgues (2015)
7	Infrastructure and logistics challenges	2	Milani, Mohr and Sandri (2021), Sandanayake, Bouras and Vrcelj (2022)
8	Complexity of sustainable design	2	Zavadskas, Šaparauskas and Antucheviciene (2018), Cascone, Parisi and Caponetto (2024)
9	Measurement and verification issues	2	Moshood, Rotimi and Shahzad (2024), Dobrucali et al. (2024)
10	Limited availability of green materials	3	Buswell et al. (2018), Ouf and Issa (2017), Habert et al. (2020)

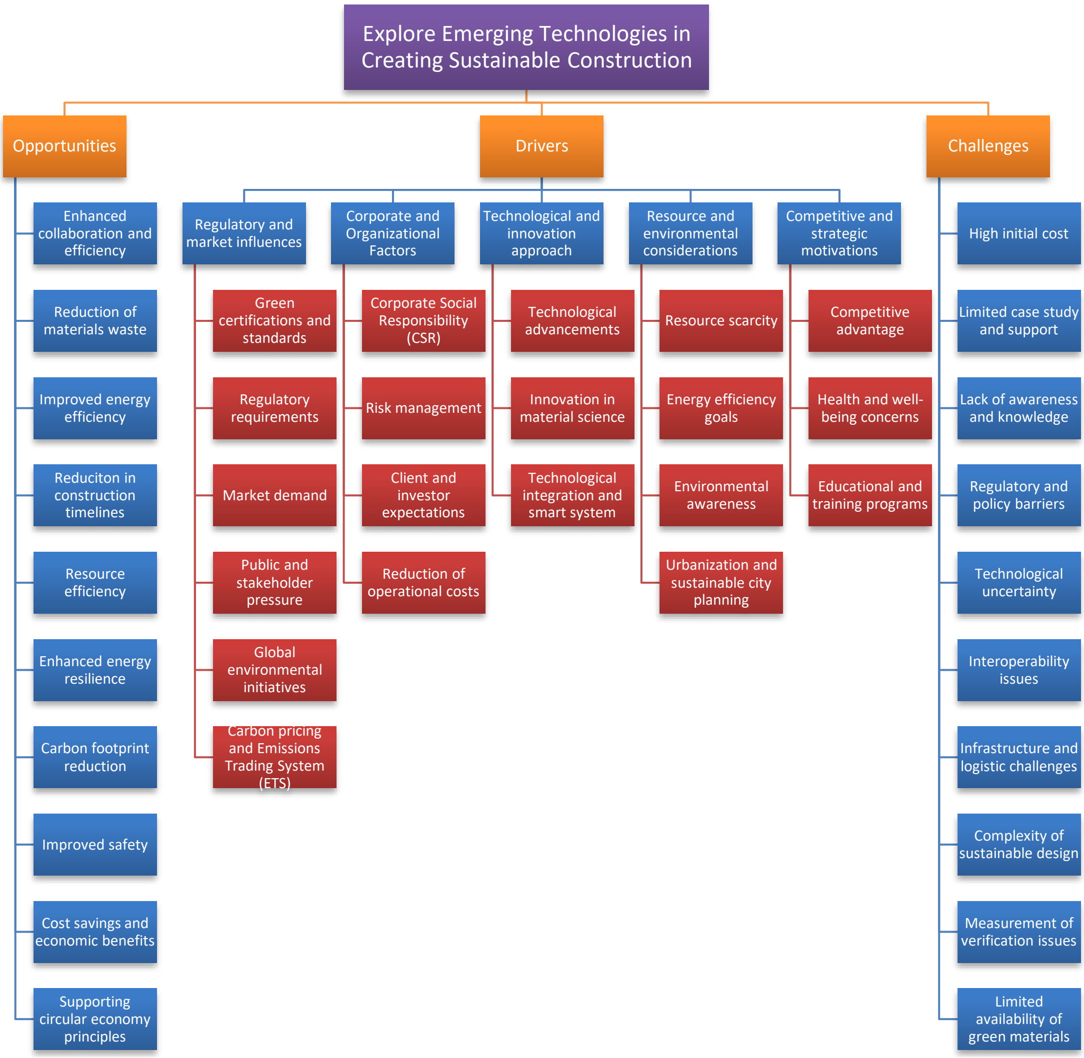

Figure 2.1: Framework of Opportunities, Drivers and Challenges of Using Emerging Technologies to Create Sustainable Construction.

CHAPTER 3

METHODOLOGY AND WORK PLAN

3.1 Introduction

Research is a systematic investigation designed to generate generalisable knowledge through structured data collection and analysis (Leedy and Ormrod, 2016). This chapter will examine and choose the methodologies used for this research based on the characteristics of the qualitative and quantitative approaches. Moreover, it will be discussed in detail to analyse the design and ensure the collected data and all the information are systematically developed regarding the emerging technologies in creating sustainability in the construction industry.

3.2 Research Method

Research methodology is a well-planned and effective approach that is employed to solve the research problem by logically implementing the most appropriate and practical method (Jansen and Warren, 2020), analysing the gathered data, and making conclusions. It involved identifying and evaluating approaches, paying attention to constraints and resources, stating assumptions and consequences, and comparing the possibilities with the 'in-between' at the 'edge' of the existing knowledge. The two broad categories of research are qualitative research and quantitative research (Mohajan and Nazrul, 2009). Quantitative research will be highly suitable as compared to qualitative research as it quantified data and generalized outcomes to a larger group of people, suitable for large sample sizes and statistical analysis. The method of data collection is through such as population surveys, questionnaires as well as opinion polls (Chrysochou, 2017).

3.2.1 Quantitative Research Approach

The quantitative research approach is an empirical method of study that aims at measuring data and using statistics to arrive at conclusions. It is the process of gathering quantitative data using questionnaires, experiments, or observations to make inferences about a larger population. Quantitative research is widely applied in social sciences, economics, and health sciences because it provides objective and replicable data. The approach is most effective for use in research that involves assessment of variables, examination of connections between those variables, and identification of cause and effect (Babones, 2016).

3.2.2 Justification of Selection

Based on the previous discussion, quantitative methods are adopted. According to Barroga and Matanguihan (2022), the quantitative analysis explored the relationship among variables by investigating the hypothesis. It involved gathering and evaluating numerical data using questionnaires, surveys, experiments and observational studies. The questionnaire is a common example of quantitative research that can be conducted differently.

A questionnaire is used to collect quantitative data in a structured manner, and it is useful for large sample sizes as it can reach many respondents in a shorter time. Since the target participants involve construction participants such as client, consultants as well as contractors, a large amount of quantitative data is crucial for reasonable statistical data analysis. This is because a small number of respondents may not accurately reflect the entire population of construction participants. Thus, the result can be generalised in Klang Valley, Kuala Lumpur by using the quantitative method.

3.3 Research Design

Research design is defined as the general approach that a researcher applies to ensure that the various elements of the study are logically connected and form a consistent whole (Ishtiaq, 2019). This framework contributed to enhance the research problem by providing a framework for data collection, measurement and analysis. It entailed decisions regarding the types of research for instance, experimental, correlational or descriptive, the selection of the sample, the mode of data collection and the instruments of data analysis. A good research design assisted in making sure that the results of the study are credible, consistent, and extendable to other settings. The outline of this research is depicted in Figure 3.1.

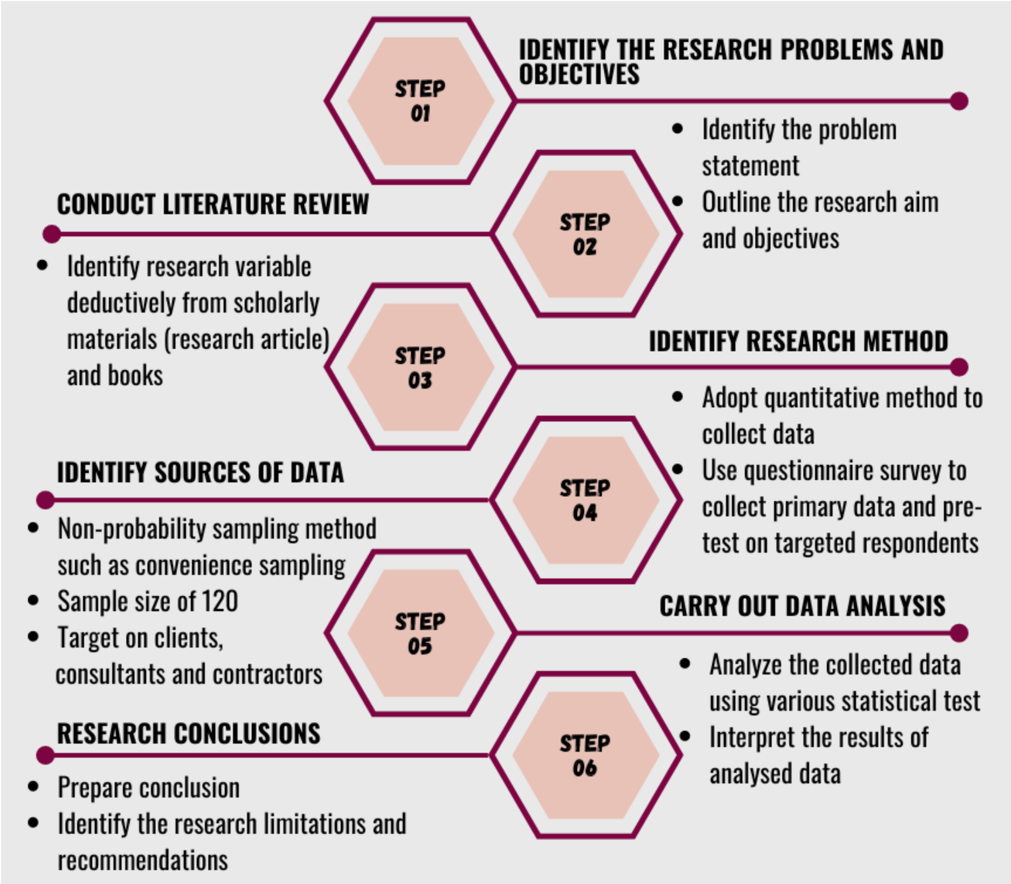

Figure 3.1: Research Flowchart

3.4 Sampling Design

The sampling technique on the other hand is defined as the plan or the method used in choosing a sample from the population for research. The purpose of this is to make sure that the sample is an ideal representation of the population so that the conclusions drawn from the sample are generalisable to the entire population (Tillé and Wilhelm, 2017). Sampling designs can vary depending on the research objectives. They can include methods such as simple random sampling, stratified sampling, cluster sampling, and systematic sampling whereby each sampling has its advantages and limitations. Hence, a well-chosen sampling design is important for minimizing biases and errors in the research process, thereby improving the reliability and validity of the study's findings (Tillé and Wilhelm, 2017).

3.4.1 Sampling Method

Certain methods are used in research to choose a smaller part of the population to represent the whole. They can be divided into probability and non-probability sampling methods as shown in Figure 3.2.

After comparing these two sampling methods, the non-probability sampling method is more suitable specifically the convenience sampling. convenience sampling will also be chosen due to its effectiveness in exploring or gathering preliminary insights. It allowed researchers to quickly collect data and identify trends or patterns that can be explored further in more rigorous studies (Chan *et al.*, 2018). According to Osunsanmi et al. (2020), it has utilized a convenience sampling technique in obtaining the data from the construction workers due to its ability to gather data within a short period of time. Also, the researcher mentioned that convenience sampling is used to meet particular criteria of the study which the respondents are actively involved with construction projects with a good understanding of the emerging technologies. Hence, convenience sampling can help to reduce costs by focusing on participants who are easily accessible to the researchers (Durdyev, Omarov and Ismail, 2017).

Furthermore, snowball sampling will be carried out after the convenience sampling. Snowball sampling relies on initial participants to recruit others from their networks. This technique is useful for accessing hard-to-reach or specialized populations (Naderifar, Goli and Ghaljaie, 2017). According to Maqbool et al. (2023), the researcher utilized snowball sampling to collect data through the researcher’s professional network of construction colleagues and university alumni. Hence, this can increase the number of questionnaires distributed which will then increase the response rate of data collection.

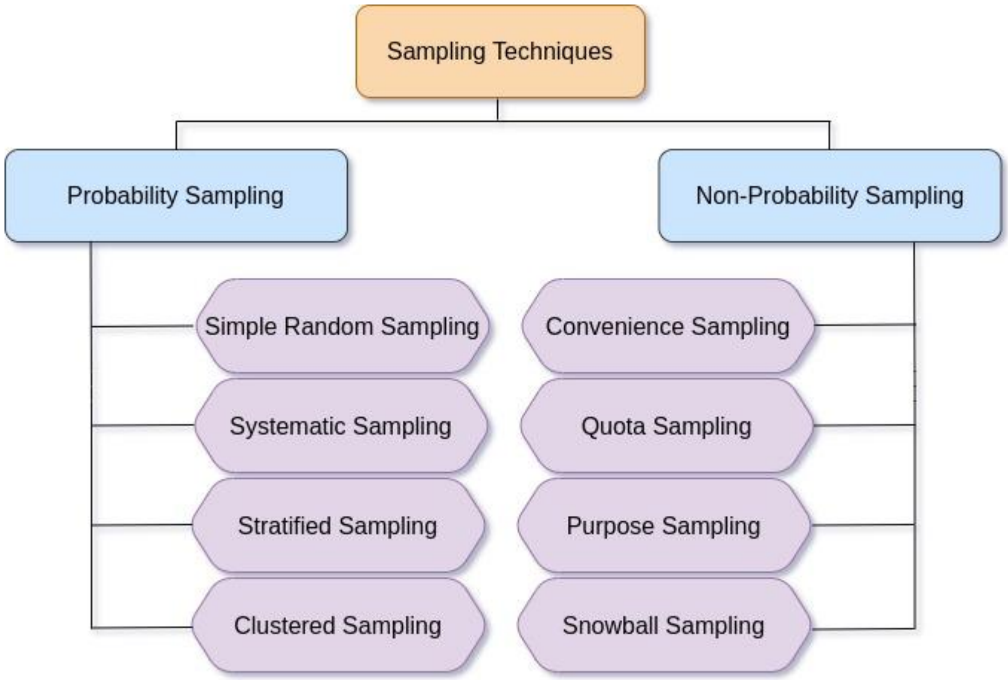

Figure 3.2: Types of Sampling Methods.

Source: Padhai Time, 2022

3.4.2 Sampling Size

This research adopted the Central Limit Theorem (CLT) to justify the minimum required sample size. The CLT suggested that when the sample size reaches approximately 30 or more, the sampling distribution of the mean tends to follow a normal distribution, thereby enabling the use of parametric statistical techniques (Turney, 2022). In this research, a minimum sample size of 120 was targeted with a minimum of 30 respondents for each sampling group which involved developers, consultants and contractors, leading to a baseline requirement of 90 participants to satisfy the assumptions of the CLT.

Nonetheless, the nature of this study also calls for the use of Factor Analysis to reduce and interpret the 20 identified drivers of emerging technologies that improve construction sustainability. According to the Rule of 5, at least five respondents per item are recommended to ensure the stability and validity of the factor structure (Bujang *et al.*, 2012). As such, the minimum overall sample size was set at 100 (5 x 20 variables) to align with this rule and to support meaningful statistical interpretation.

3.4.3 Target Respondents

The target respondents for this study are construction practitioners such as developers, consultants and contractors who are directly involved in the construction industry and familiar with sustainable practices and emerging technologies in Malaysia mainly focusing on the Klang Valley area as Klang Valley is a key metropolitan area in Malaysia. Besides, to ensure broader data representation and enhance the generalizability of the findings, the study included participants from other regions across the country including Northern region, Southern region, East Coast, as well as Sabah and Sarawak. The selection of this demographic is based on their direct relevance to the research objectives, which aim to explore the use of emerging technologies to create a sustainable construction environment.

3.5 Data Collection Method

3.5.1 Questionnaire Design

A questionnaire design usually outlines the purpose of the research to assess the construction practitioners' opinions on the integration of emerging technologies in the construction industry to create sustainability as well as the factors that influence the opinions or decisions. The online questionnaire contained four sections such as demographic background, opportunities, drivers and challenges sections. The first section is designed to gather practitioners' demographic background to know who the participants are involved. The second section is related to the first objective of this research which is on the opportunities of emerging technologies. Section three of the questionnaire was drafted to contain the rating of 20 drivers of using emerging technologies. The question will be based on the five-point Likert scale which the rating is scale from 1 to 5 as it is easier to analyse, yet it may limit respondents' input. For example, 1 refers to strongly disagree and 5 refers to strongly agree. Lastly, section four will be set to ask respondents about the challenges of using emerging technologies nowadays. Same as previous section, this section using rating scale where 1 refers to no challenge and 5 refers to major challenge.

3.5.2 Pre-Test

A pre-test is a small-scale trial run of the designated questionnaire to identify potential problems in question design, instructions, or layout before the full-scale survey is conducted. 2 participants from each group are sufficient to carry out the pre-test. The questionnaire will be distributed to 2 clients, 2 consultants and 2 contractors. After the respondents completed the pre-test, feedback will be gathered based on their experience of whether any questions were unclear, difficult to answer, or confusing. Based on the feedback and data analysis, necessary adjustments will be made to improve the questionnaire.

3.6 Data Analysis

Following the distribution of the questionnaire to the targeted respondents and the achievement of the desired response rate, the gathered data was effectively and comprehensively evaluated. Data analysis involves data collection, cleaning, interpretation, and visualization. Several key techniques that support the overall efficacy and legitimacy of the study are utilized in the analysis to gather information. In this research, a Statistical Package for Social Science (SPSS) will be used to analyze further all the data collected through the quantitative method. The selected data analysis methods to perform the data obtained are listed below:

i. Normality Test
ii. Cronbach's Alpha Reliability Test
iii. Mean Score and Standard Deviation
iv. Kruskal-Wallis Test
v. Spearman's Correlation Test
vi. Factor Analysis

3.6.1 Normality Test

In the construction industry, research often involves analyzing data related to project timelines, costs, safety incidents, and productivity metrics. These data are typically subjected to various statistical analyses to identify trends, correlations, or causality. The validity of these analyses depends heavily on whether the underlying data follow a normal distribution. If the data are not normally distributed, the researcher might need to apply non-parametric tests such as Kruskal-Wallis and Spearman's Correlation test. According to Mohd Razali and Bee Wah (2011), the researcher compared all normality tests in terms of power against the symmetric non-normal distributions. It shows that the Shapiro-Wilk test is the most suitable normality test among other tests as it is restricted to a sample size of less than 50 and ranked as the highest power with the lowest total rank as compared to other tests. Nevertheless, a sample size of less than 30 will decrease the power by 40% when the significance level is 5%. In this research, a normality test is used to check the validity of data and whether it is normal.

3.6.2 Cronbach's Alpha Reliability Test

Cronbach's Alpha is a measure of internal consistency, often used in research to determine the reliability of a group of scale or test items. It assesses how effectively a set of items measures a single, unidimensional latent aspect. The value of Cronbach's Alpha ranges from 0 to 1 as shown in Table 3.1, where higher values indicate greater internal consistency. A common threshold for acceptable reliability is 0.7 or above, this can be different depending on the context and field of study (Taber, 2018).

Cronbach's Alpha is frequently used in studies to ensure that the items within a scale are consistently measuring the intended construct. For instance, in a study assessing the adoption of sustainable construction practices, a questionnaire might include multiple items to gauge different aspects of sustainability awareness. Cronbach's Alpha would then be used to verify that these items collectively provide a reliable measure of sustainability awareness (Cho and Kim, 2015).

In this research, Cronbach's Alpha Reliability test is adopted to test the three variables group, which are the objectives of this study. This test is useful to check the reliability of each variable group and the alpha score must be more than 0.6 as shown in Table 3.1 to ensure that each group of variables is reliable and consistent to conduct the study.

Table 3.1: Range of Cronbach's Alpha Reliability

Cronbach's Alpha Score	**Level of Reliability**
0.0 – 0.20	Less Reliability
0.20 – 0.40	Rather Reliability
0.40 – 0.60	Quite Reliability
0.60 – 0.80	Reliability
0.80 – 1.00	Very Reliability

3.6.3 Mean Score and Standard Deviation

Mean score and standard deviation are a statistical technique used to rank the variables, or prioritise the variables based on average scores. It is often applied in survey research, particularly when respondents are asked to rate or rank several items according to importance, preference, or satisfaction. The mean ranking provides a straightforward way to aggregate and compare the relative standing of each item across all respondents. According to Darko, Zhang and Chan (2017), the researcher applied mean score and standard deviation to determine the most critical drivers for green building in the construction industry. When two or more factors carried the same mean score, the factor with the lowest standard deviation will be given the higher rank (Darko *et al.*, 2017).

In this research, mean score and standard deviation will be applied to prioritize the opportunities, drivers and challenges as perceived by the practitioners using the five-point Likert scale on using emerging technologies to create sustainable construction. After generating the mean value, the variables can be ranked according to their mean value. The higher mean value will have higher ranking which will be regarded as most significant variable. The mean value ($\bar{x}$) and standard deviation (σ) are computed using the formula as below:

3.6.4 Kruskal-Wallis H Test

The Kruskal-Wallis H test is a non-parametric statistical test that determines if there are statistically significant differences among the medians of three or more independent groups. It is an extension of the Mann-Whitney U test to multiple groups and is applied when the assumptions of the one-way ANOVA are not satisfied, notably the assumption of normality (Hecke, 2012).

In this research, the Kruskal-Wallis H test can be useful for analysing ordinal data that do not meet the parametric assumptions. For example, it can help to determine whether the sustainability outcomes differ significantly across technologies. It is a test to find out significant differences between three variable groups, which are the opportunities, drivers and challenges of using emerging technologies between clients, consultants and contractors.

In order to carry out the conduct of the Kruskal-Wallis H test, all data collected will be ranked from lowest to highest, followed by calculating the sum of ranks for each group. Finally, compute the Kruskal-Wallis H statistic using the formula below:

There are two hypotheses generated for this test:

Null hypothesis (H_0): There is no significant difference between the groups, $p>0.05$.

Alternative hypothesis (H_1) = There is significant difference between the groups, $p \leq 0.05$.

3.6.5 Spearman's Correlation Test

Spearman's rank correlation coefficient which often denoted as ρ (rho) or r_s is a non-parametric measure of the level of intensity and direction of the relationship between two ranked variables. Spearman's correlation does not assume any specific distribution and can handle ordinal data or data that are not normally distributed (Eden, Li and Shepherd, 2022). The correlation coefficient r_s ranges from -1 to 1 where $r_s = 1$ refers to perfect positive correlation, $r_s = -1$ refers to perfect negative correlation, and $r_s = 0$ refers to no correlation.

The analysis provides insights on how strongly each driver correlates with different sustainability-related challenges, offering a deeper understanding of interdependencies that could influence successful implementation in the construction sector. In order to conduct Spearman's correlation, all the raw data will be converted into ranks and find the difference between the ranks of each pair. Then, apply the formula below to compute the Spearman's correlation coefficient.

Grading Standards	Correlation Degree
$\rho = 0$	no correlation
$0 < \lvert\rho\rvert \leq 0.19$	very week
$0.20 \leq \lvert\rho\rvert \leq 0.39$	weak
$0.40 \leq \lvert\rho\rvert \leq 0.59$	moderate
$0.60 \leq \lvert\rho\rvert \leq 0.79$	strong
$0.80 \leq \lvert\rho\rvert \leq 1.00$	very strong
1.00	monotonic correlation

Figure 3.3: Grading Table of Spearman Correlation Coefficient (ρ)

Source: Yan et al. (2019)

3.6.6 Factor Analysis

Factor analysis is a statistical technique used to identify the underlying relationships between a large set of variables. It helps to reduce a large number of variables into fewer factors, which are unobservable variables that influence the observed data. This technique is particularly advantageous when dealing with complex data sets, as it simplifies the data structure, making it easier to interpret (Hwang and Ng, 2013).

In this research, Exploratory Factor Analysis (EFA) is particularly valuable when there is no prior theory about the data and seeks to explore the underlying factors (Watkins, 2018). For example, factor analysis can be used to group related emerging technology of 20 drivers into 5 or 6 latent factors which will then be analysed to understand how different technologies contribute to overall sustainability. To ensure the appropriateness of data for EFA, the correlations should exceed 0.30 while the Kaiser-Meyer-Olkin (KMO) value should not be less than 0.50 as it indicates that the correlation matrix is not factorable. Also, a measurement error will decrease the reliability of the variables as well as the correlation between the variables. Therefore, it is not encouraged to consider EFA if the reliability of variables is less than 0.70 (Watkins, 2018).

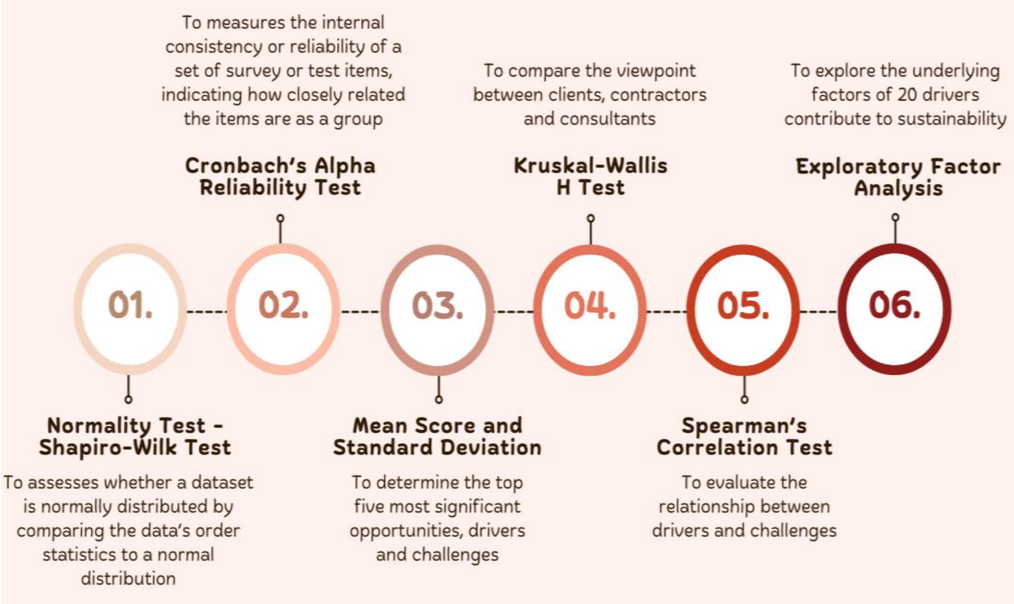

Figure 3.4: Data Analysis

3.7 Summary

To sum up, this chapter identifies the method to be used for this study, which is the quantitative research method. A questionnaire will be distributed to the respondents to collect the data. The targeted respondents are practitioners in Malaysia with a sample size of 120 which includes clients, consultants and contractors. A pre-test will be carried out before distributing the questionnaire survey involving of 2 respondents from each sample group to ensure that the questionnaire is well-designed. In addition, a non-probability sampling method is adopted for this study such as convenience sampling and snowball sampling. There are six techniques have been chosen to analyze the collected data which are Normality test, Cronbach's Alpha Reliability test, Mean Score and Standard Deviation, Kruskal-Wallis H test, Spearman's Correlation test and Factor Analysis. Thus, this chapter helps readers to have a better understanding of the methods or techniques used in data collection as well as data analysis for this study.

CHAPTER 4

RESULTS AND DISCUSSION

4.1 Introduction

In this section, the results of data collected from quantitative research were presented. The implications of the findings were examined, recognising their importance in advancing comprehension of the drivers and challenges of adopting emerging technologies to achieve the research objectives. The collected data was reorganized, processed and tabulated using SPSS Statistics.

4.2 Outcome of Pre-Test

The pre-test survey achieved a 100% response rate, comprising two clients, two consultants, and two contractors. This complete participation reflects effective engagement across all key stakeholder groups, thereby enhancing the reliability of the results. The successful completion of the pre-test further confirmed that the questionnaire was well-structured and required no revisions. This conclusion was based on respondent feedback, which affirmed that the questions were clear, relevant, and easy to comprehend. The strong level of participation and positive outcomes at this preliminary stage suggest that the survey instrument is both reliable and appropriate for broader application (Ranganathan, Caduff and Frampton, 2024).

4.3 Questionnaire Response Rate

Following the positive outcomes of the pre-test, the finalized questionnaire was distributed to the targeted participants via email and various social media platforms, including Instagram, MS Teams, and WhatsApp. A total of 280 questionnaires were disseminated among construction professionals across Malaysia. Over seven weeks, 120 valid responses were collected, resulting in a response rate of 42.86%. According to Fincham (2008), a response rate of approximately 60% is generally recommended for most research endeavours. However, achieving high response rates can be challenging in practical situations, particularly when engaging with hard-to-reach populations. In such cases, a response rate exceeding 30% is still considered acceptable for producing valid statistical analyses, provided the sample is representative and appropriate weighting or adjustment techniques are applied to account for potential biases (Le Masson, 2023).

4.4 Profile of Respondents

The respondents are fairly evenly distributed across different construction roles, with 41 participants (34.2%) representing clients, 40 participants (33.3%) representing contractors, and 39 participants (32.5%) representing consultants. This balanced distribution ensures diverse perspectives from key stakeholders in the construction industry.

In terms of professional specialization, the majority of respondents are Quantity Surveyors (48 participants, 40.0%), followed by M&E Engineers (19 participants, 15.8%), Architects (18 participants, 15.0%), and those involved in Project/Construction Management (18 participants, 15.0%). C&S Engineers constituted 14.2% (17 participants) of the sample. This spread reflects a strong representation from both cost management and technical disciplines.

The majority of the respondents (75 participants, 62.5%) are affiliated with the private sector, while 45 participants (37.5%) are from the public sector. This distribution indicates a slight leaning towards private sector insights into construction practices.

Regarding educational attainment, most respondents possess a Bachelor's degree (91 participants, 75.8%), with 23 participants (19.2%) holding a postgraduate qualification (Master’s or Doctorate). Only 6 participants (5.0%) have a diploma as their highest qualification. This high level of academic achievement suggests that the respondents are well-equipped with the necessary theoretical knowledge and professional expertise.

In terms of professional experience, more than half of the respondents (67 participants, 55.8%) have less than five years of experience, followed by those with 5 to 10 years (29 participants, 24.2%), 11 to 20 years (17 participants, 14.2%), and more than 20 years of experience (7 participants, 5.8%). This indicates a relatively youthful respondent group, with valuable contributions from experienced professionals.

A majority of the respondents (81 participants, 56.3%) primarily operate in the Klang Valley, the central economic hub of Malaysia. The remainder are distributed across other regions: Southern Region (18.8%), Northern Region (11.8%), East Coast (5.6%), Sarawak (4.2%), and Sabah (3.5%).

Respondents have experience across various project types, with the largest proportion involved in residential projects (71 participants, 37.6%), followed by commercial (55 participants, 29.1%), industrial (38 participants, 20.1%), infrastructure (13 participants, 6.9%), and environmental projects (12 participants, 6.3%).

When assessing familiarity with sustainable construction technologies, most respondents demonstrate basic to moderate levels of experience: 50 participants (41.7%) have basic experience, and 16 participants (13.3%) are proficient users. Additionally, 4 participants (3.3%) are experts actively utilizing these technologies. Conversely, 43 participants (35.8%) have merely heard of these technologies, while 7 participants (5.8%) are unfamiliar. This shows an encouraging trend towards the adoption of sustainable practices, although there is still room for increased proficiency. Table 4.1 summarises the demographic and professional characteristics of the respondents.

Table 4.1: Demographic Profile of Respondents

Parameter	Description	Total	Percentage (%)
Construction Roles	Client	41	34.2
	Contractor	40	33.3
	Consultant	39	32.5
Industry background	Quantity Surveyor	48	40.0
	Architect	18	15.0
	M&E Engineer	19	15.8
	C&S Engineer	17	14.2
	Project/Construction Management	18	15.0
Types of Organization	Public Sector	45	37.5
	Private Sector	75	62.5

Academic qualification	Diploma	6	5.0
	Degree	91	75.8
	Postgraduate Degree	23	19.2
Working experience	Less than 5 years	67	55.8
	5 – 10 years	29	24.2
	11 – 20 years	17	14.2
	More than 20 years	7	5.8
Primary Operate Region	Klang Valley	81	56.3
	Northen Region	17	11.8
	Southern Region	27	18.8
	East Coast	8	5.6
	Sabah	5	3.5
	Sarawak	6	4.2
Types of Projects Involved	Residential	71	37.6
	Commercial	55	29.1
	Industrial	38	20.1
	Infrastructure	13	6.9
	Environmental	12	6.3
Experience with sustainable construction technologies	Unfamiliar with these technologies	7	5.8
	Heard of these technologies	43	35.8
	Have basic experience using these technologies	50	41.7
	Proficient in using these technologies	16	13.3
	Expert and actively using these technologies	4	3.3

4.5 Scale Reliability

Reliability analysis was conducted using Cronbach's Alpha to evaluate the internal consistency of the items within each questionnaire construct: opportunities, drivers and challenges associated with adopting emerging technologies in the construction industry. Table 4.2 shows the summary of reliability analysis on constructed items.

According to Taber (2018), Cronbach's Alpha value above 0.7 is considered acceptable, with values above 0.8 representing good reliability, and those above 0.9 denoting excellent internal consistency. Therefore, the values obtained demonstrated that the questionnaire items reliably measure their respective constructs without redundancy or inconsistency.

Furthermore, internal consistency ensures that all items within a construct are sufficiently correlated and can be interpreted as representing a single latent factor (Kang, McNeish and Hancock, 2016). Thus, the measurement scales used in this study are statistically valid and suitable for further analysis.

Table 4.2: Summary of Reliability Analysis on Constructed Items

Variables	Number of Items	Alpha Value
Opportunities of Emerging Technologies on Sustainability	10	0.814
Drivers of Emerging Technologies that Improve Sustainability	20	0.915
Challenges of Adopting Emerging Technologies	10	0.857

4.6 Normality Test – Shapiro-Wilk Test

The SPSS analysis revealed a p-value of 0.000 in both the Shapiro-Wilk and Kolmogorov-Smirnov tests. As the p-values were less than 0.05, the null hypothesis (H_0), which assumes that the data is normally distributed, was rejected. This indicates that the data significantly deviates from a normal distribution, thereby validating the alternative hypothesis (H_1).

In accordance with Mishra et al. (2019), when the assumption of normality is violated, the application of non-parametric tests is recommended to maintain the integrity of statistical analysis. Consequently, this study employed non-parametric methods such as the Kruskal-Wallis H test and Spearman's rank correlation, which are more suitable for skewed or non-normal distributed data.

4.7 Opportunities of Emerging Technologies on Sustainability in the Construction Industry

4.7.1 Ranking Using Mean Scores and Standard Deviation

The descriptive analysis of the "Opportunities" construct was conducted to assess the perceived effectiveness of different emerging technologies in enhancing sustainability within the construction industry. These results reflect industry-wide recognition of the environmental and economic benefits that digital and smart technologies bring to construction, consistent with prior research (Thirumal *et al.*, 2024). Based on the 120 respondents, the mean scores were ranked in descending order as shown in Table 4.3. When two or more variables have the same mean score, the variable with the lower SD will be ranked higher.

The highest-ranked opportunity, with an overall mean score of 4.25, was the implementation of smart water-saving systems, energy-efficient appliances, and advanced waste management strategies (O5). This finding highlights the construction industry's recognition of resource efficiency as a central pillar of sustainable development. Clients rated this item the highest (mean = 4.32), reflecting their growing concern for long-term operational savings and environmental responsibility. This result aligns with Maqbool and Amaechi (2022), who noted that technologies which reduce water and energy consumption are critical to achieving sustainability in construction projects. These systems also contribute to certifications such as LEED and Malaysia's Green Building Index (GBI), increasing the market appeal and environmental performance of buildings (Mat Isa *et al.*, 2023).

Closely following in second place was the opportunity to enhance real-time collaboration through digital platforms such as Building Information Modelling (BIM) and cloud-based technologies (O1), with an overall mean of 4.23. Consultants rated this item the highest (mean = 4.28), possibly due to their involvement in project coordination and data integration across disciplines.

These digital tools play a critical role in reducing delays, enhancing communication, and minimizing rework. Maqbool and Amaechi (2022) emphasized that the integration of smart systems such as BIM significantly improves construction performance by streamlining processes and increasing efficiency. Olawumi and Chan (2018) also highlighted that BIM adoption leads to better resource management and supports environmentally conscious decision-making throughout a project's lifecycle.

The third-ranked opportunity was the use of 3D printing and prefabrication technologies to produce precise quantities of construction materials, thereby reducing waste and optimizing material use (O2), also with a mean score of 4.23. Contractors rated this highest (mean = 4.32), which is consistent with their direct experience in on-site construction efficiency. Prefabrication reduces environmental impact through controlled production environments, while 3D printing enhances precision and reduces excess inventory. Bedarf et al. (2021) found that additive manufacturing can reduce construction waste by up to 60%, contributing significantly to sustainable construction goals. These methods also support faster project delivery and improve quality assurance, making them particularly attractive in urban or resource-constrained environments.

Ranked fourth overall, with a mean score of 4.23, was the opportunity to utilize digital tools that optimize resource use, minimize rework, and enhance project profitability (O9). Clients gave this item the highest rating (mean = 4.34), indicating strong interest in cost-effective digital solutions. Such tools, including construction management software and IoT-based monitoring systems, provide real-time data that supports informed decision-making and efficient use of materials and labor. Prabhakaran, Mahamadu and Mahdjoubi (2022) underscored that digital technologies contribute to improved procurement processes, reduced project delays, and better financial control. These outcomes align well with broader sustainability and productivity objectives in the construction sector.

The fifth-ranked opportunity was the integration of smart energy management systems and energy-efficient building materials (O3), which recorded an overall mean score of 4.20. This item received particularly high scores from clients and contractors, who acknowledged the long-term benefits of reducing electricity consumption and enhancing energy efficiency. Although consultants gave slightly lower ratings, possibly due to implementation complexity, the overall perception remained positive. Yusof et al. (2021) emphasized that incorporating energy-saving technologies during the design stage significantly improves building performance over its lifecycle. These systems not only reduce greenhouse gas emissions but also contribute to operational savings and regulatory compliance, particularly in countries with increasing energy efficiency mandates.

4.7.2 Kruskal-Wallis H Test

To determine whether the differences in perceptions among clients, contractors, and consultants were statistically significant, the Kruskal–Wallis H test was conducted for each opportunity item. The results indicated that all p-values were above 0.05, suggesting that there were no statistically significant differences among the three stakeholder groups as shown in Table 4.3. This implies a shared understanding and agreement on the importance of each opportunity, regardless of professional background. The absence of significant variation among groups supports findings by Klufallah, Ibrahim and Moayedi (2019), who noted a convergence of stakeholder perspectives in Malaysian sustainable construction practices. This alignment may be attributed to the influence of national policies such as the Construction Industry Transformation Programme (CITP) and Industry4WRD, which have helped unify industry standards and sustainability goals.

Table 4.3: Mean and Ranking of Opportunities of Emerging Technologies on Sustainability

No.	Opportunities	Overall (N=120)			Client (N=41)			Contractor (N=40)			Consultant (N=39)			Chi-square	P-value
		Mean	SD	Rank	Mean	SD	Rank	Mean	SD	Rank	Mean	SD	Rank		
O5	Smart water-saving systems, energy-efficient appliances and advanced waste management strategies to minimize the use of water, energy and raw materials	4.25	0.638	1	4.32	0.650	2	4.25	0.630	3	4.18	0.644	3	1.168	0.558
O1	Access real-time project updates and share changes instantly using digital platforms like BIM or cloud technology	4.23	0.590	2	4.24	0.624	5	4.18	0.636	5	4.28	0.510	1	0.551	0.759
O2	3D printing or prefabrication to produce only the exact materials needed, reducing the amount of excess material on site	4.23	0.683	3	4.22	0.759	6	4.32	0.656	1	4.15	0.630	5	1.469	0.480
O9	Digital tools optimize resource use, reduce waste and minimize rework, ultimately lowering overall costs and improving project profitability	4.23	0.692	4	4.34	0.728	1	4.15	0.662	6	4.18	0.683	4	2.486	0.289
O3	Smart energy management systems and energy-efficient building materials to reduce electricity use throughout the building's lifecycle	4.20	0.656	5	4.29	0.680	3	4.27	0.599	2	4.03	0.668	8	4.426	0.109
O7	Carbon capture technology and low-emission materials to actively reduce the amount of carbon produced during construction	4.20	0.717	6	4.12	0.678	9	4.25	0.776	4	4.23	0.706	2	1.161	0.560
O8	Smart PPE that alerts to potential hazards, while drones and robotics handle risky tasks	4.17	0.771	7	4.29	0.782	4	4.13	0.791	8	4.08	0.739	7	2.684	0.261
O10	Building that is designed for easy disassembly, with materials that can be reused or recycled after the building's lifecycle, reducing waste and supporting a circular economy	4.12	0.676	8	4.20	0.679	7	4.15	0.700	7	4.00	0.649	9	2.197	0.333
O6	Hybrid renewable energy systems, along with energy storage to ensure continuous power, even during power outages	4.10	0.726	9	4.17	0.738	8	4.13	0.757	10	4.00	0.688	10	1.859	0.395
O4	Drones are used for surveying, robotics for repetitive tasks and prefabricated parts are delivered ready to install, which shortens the overall construction time	4.09	0.698	10	4.07	0.721	10	4.13	0.791	9	4.08	0.580	6	0.530	0.767

4.8 Drivers of Emerging Technologies that Improves Construction Sustainability

4.8.1 Ranking Using Mean Scores and Standard Deviation

As shown in Table 4.4, most of the drivers have a mean score of >4.00, which is considered notable in the rating scale. The five leading drivers of emerging technologies are "reduction of operational costs", "regulatory requirements", client and investor expectations", technological integration and smart systems" and "market demand".

The highest-ranked driver across all respondent groups **is** "reduction of operational costs" (Mean = 4.24), reflecting its universal importance among clients, consultants, and contractors. This finding aligns with the study by Prabhakaran, Mahamadu, and Mahdjoubi (2022), which found that digital tools such as BIM, prefabrication, and automation contribute to reduced rework, improved material usage, and better project scheduling — all of which significantly lower operational costs. The current study's results are further reinforced by Akbarnezhad and Xiao (2017), who emphasized that productivity gains from emerging technologies directly translate into lower labor and material costs. These empirical findings help validate our data, where cost-efficiency emerges as the dominant driver, particularly in a cost-sensitive sector like construction. Additionally, the emphasis on cost management is consistent with Waqar et al. (2023), who highlighted that economic feasibility remains a key determinant of sustainable construction success in Malaysia.

Equally ranked first (Mean = 4.23), "regulatory requirements" emerge as a powerful external influence on technology adoption. Consultants scored this driver highest (Mean = 4.26), likely due to their frequent engagement with building codes, standards, and policy interpretation. This corresponds with Jaffar et al. (2022), who assert that compliance not only enforces minimum sustainability standards but also serves as a catalyst for firms to improve their environmental performance and corporate reputation. Our findings resonate with this perspective, especially considering Malaysia's national frameworks such as the Construction Industry Transformation Programme (CITP) and Industry4WRD**,** which actively promote digital technology use in meeting sustainability benchmarks (CIDB, 2020). Thus, the strong mean score obtained in this study validates the influence of government-led regulations in driving digital and sustainable transformation in the construction sector.

The third-ranked driver**,** “client and investor expectations” (Mean = 4.19), emphasizes the increasing role of stakeholder influence in project execution. Contractors and consultants gave relatively high ratings to this factor, suggesting that construction strategies are increasingly shaped by ESG (Environmental, Social, and Governance) standards imposed by clients and financiers. This aligns with the findings of Mavi et al. (2021a), who documented that stakeholder pressure, particularly from investors concerned with sustainability performance, has led to a significant shift in adopting green and digital technologies. The mean score observed in this study reflects this trend, where expectations from clients now act as a strategic force in driving technology integration.

In fourth place **is** “technological integration and smart systems” (Mean = 4.16), with consultants rating it highest (Mean = 4.26). This demonstrates growing industry interest in digital ecosystems such as IoT, AI, and cloud-based platforms. These technologies not only enhance project efficiency but also support real-time monitoring and predictive maintenance. Our results are supported by Zhang et al. (2023), who noted that smart construction systems improve productivity and sustainability by enabling proactive decision-making on-site. Similarly, Olawumi and Chan (2018) concluded that firms using integrated technologies perform significantly better in sustainability metrics. Thus, the strong mean score in this study is substantiated by these empirical findings, emphasizing the value of technological integration in modern construction practice.

The fifth-ranked driver, “market demand” (Mean = 4.10), highlights the broader industry shift towards sustainability and digital innovation. The consistency in ratings across all respondent groups indicates a shared perception that the construction market is undergoing transformation due to global sustainability targets and evolving client preferences. This is consistent with Maqbool and Amaechi (2022), who argue that industry-wide trends are compelling companies to innovate in order to remain competitive. The data from this study confirms this outlook, as the construction professionals surveyed perceive market pressures as a critical factor influencing technology adoption.

4.8.2 Kruskal-Walis H Test

It was applied to determine whether clients, contractors, and consultants significantly differed in their evaluation of each of the 20 listed drivers. As shown in the Table 4.4, all p-values were greater than 0.05, indicating that none of the differences were statistically significant. This consistency suggests a strong alignment across the construction industry in terms of what is valued as key motivators for adopting emerging technologies in sustainability practices. Klufallah, Ibrahim and Moayedi (2019) described such convergence as indicative of a maturing industry where environmental, economic, and technological imperatives are recognized across all project roles. The absence of significant variation also implies that any strategic interventions or policy frameworks designed to promote technology adoption can be applied uniformly across stakeholder groups, simplifying implementation and fostering cross-disciplinary collaboration.

Table 4.4: Mean and Ranking of Drivers of Emerging Technologies that Improve Construction Sustainability

No.	Drivers	Overall (N=120)			Client (N=41)			Contractor (N=40)			Consultant (N=39)			Chi-square	P-value
		Mean	SD	Rank	Mean	SD	Rank	Mean	SD	Rank	Mean	SD	Rank		
D10	Reduction of operational costs	4.23	0.719	1	4.22	0.852	1	4.27	0.716	1	4.21	0.570	4	0.558	0.757
D2	Regulatory requirements	4.23	0.727	2	4.17	0.629	2	4.25	0.840	2	4.26	0.715	1	0.959	0.619
D9	Client and investor expectations	4.19	0.714	3	4.15	0.760	5	4.20	0.791	3	4.23	0.583	3	0.134	0.935
D13	Technological integration and smart systems	4.16	0.756	4	4.07	0.721	12	4.15	0.834	6	4.26	0.715	2	1.398	0.497
D3	Market demand	4.10	0.782	5	4.12	0.748	8	4.13	0.853	9	4.05	0.759	6	0.393	0.822
D15	Energy efficiency goals	4.08	0.705	6	4.10	0.735	9	3.98	0.620	18	4.18	0.756	5	3.098	0.212
D1	Green certifications and standards	4.08	0.717	7	4.17	0.738	3	4.10	0.810	10	3.97	0.584	14	2.264	0.322
D12	Innovation in material science	4.08	0.805	8	4.07	0.932	14	4.15	0.736	5	4.03	0.743	11	0.608	0.738
D16	Environmental awareness	4.08	0.894	9	4.10	1.020	11	4.10	0.871	12	4.05	0.793	7	0.575	0.750
D14	Resource scarcity	4.07	0.780	10	4.12	0.748	7	4.10	0.810	11	4.00	0.795	13	0.398	0.819
D20	Educational and training programs	4.07	0.827	11	3.98	0.935	20	4.20	0.823	4	4.03	0.707	8	1.740	0.419
D17	Urbanization and sustainable city planning	4.07	0.842	12	4.05	0.921	15	4.15	0.893	7	4.03	0.707	9	1.209	0.546
D19	Health and well-being concerns	4.06	0.833	13	4.07	0.848	13	4.08	0.944	14	4.03	0.707	10	0.510	0.775
D4	Public and stakeholder pressure	4.03	0.766	14	4.15	0.691	4	4.02	0.832	17	3.92	0.774	18	1.577	0.454
D5	Global environmental initiatives	4.03	0.777	15	4.02	0.790	16	4.13	0.757	8	3.95	0.793	16	1.117	0.572
D18	Competitive advantage	4.03	0.814	16	4.10	0.831	10	4.05	0.876	16	3.92	0.739	17	1.472	0.479
D8	Risk management	4.03	0.829	17	4.15	0.760	6	4.05	0.815	15	3.90	0.912	20	1.488	0.485
D6	Carbon pricing and emissions trading	4.01	0.739	18	3.98	0.651	18	4.10	0.871	13	3.95	0.686	15	1.630	0.443
D11	Technological advancement	3.95	0.765	19	4.02	0.790	17	3.82	0.781	20	4.00	0.725	12	1.793	0.408
D7	Corporate social responsibility	3.94	0.823	20	3.98	0.880	19	3.95	0.749	19	3.90	0.852	19	0.417	0.812

4.9 Challenges of Adopting Emerging Technologies in the Construction Industry

4.9.1 Ranking Using Mean Scores and Standard Deviation

The final section of the analysis addresses the challenges associated with adopting emerging technologies for sustainability in the construction industry. This analysis is critical in understanding the barriers that may hinder implementation, despite the known benefits of these technologies.

The mean ranking analysis revealed that the top-ranked challenge was the high initial cost of implementing emerging technologies (C1), with the highest overall mean score of 4.37. All three groups, clients (mean = 4.37), contractors (mean = 4.23), and consultants (mean = 4.51), consistently ranked this as the most significant barrier. The high up-front capital investment required for digital tools, automation, and energy-efficient systems remains a key concern, especially for firms with limited financial resources. According to Prabhakaran, Mahamadu and Mahdjoubi (2022), many construction firms are reluctant to invest in unfamiliar or untested technologies without clear, short-term returns. Similarly, Unegbu et al. (2024) emphasized that while long-term savings are substantial, the initial cost barrier is often perceived as too high, particularly for small and medium enterprises (SMEs) operating on tight budgets.

The second most significant challenge was the complexity of sustainability-oriented design and implementation (C8), with an overall mean score of 4.11. Consultants rated this slightly higher (mean = 4.23) than clients and contractors, suggesting that those directly involved in planning and design perceive more technical challenges. Sustainable construction often requires advanced interdisciplinary knowledge, integration of various systems, and adherence to multiple certification criteria. Gan et al. (2015) argue that the complexity of these systems, especially when combining new materials, digital platforms, and regulatory standards, can overwhelm teams that lack specialized expertise, resulting in design inefficiencies and delayed adoption.

In third place was the lack of awareness and knowledge (C3), with a mean of 4.10. This challenge was ranked highest by contractors (mean = 4.23), followed by clients and consultants. The finding indicates that inadequate understanding of emerging technologies' capabilities, applications, and benefits is still a prevalent issue, especially among stakeholders responsible for hands-on project delivery. This aligns with findings from (Musarat *et al.*, 2024), who noted that while awareness of sustainability has increased, technical literacy about digital construction tools remains uneven, particularly outside of urban regions or among smaller firms. Training and capacity-building programs are essential to bridging this gap.

Technological uncertainty (C5) was ranked fourth with a mean score of 4.08. Clients gave it the highest rating (mean = 4.24), showing a strong concern about investing in technologies whose performance or compatibility may not yet be proven in real-world settings. This challenge reflects the industry's cautious stance toward technological disruption, especially when long-term maintenance and interoperability are uncertain. Bedarf et al. (2021) observed that hesitation often stems from the lack of standardized implementation pathways, particularly for innovations like 3D printing and AI-driven project tools, which are still evolving. Concerns also persist regarding vendor support, long-term software reliability, and integration with existing construction workflows.

The fifth-ranked challenge was regulatory and policy barriers (C4), with a mean score of 4.08. This was especially highlighted by clients (mean = 4.20), suggesting frustration with unclear or evolving regulatory frameworks that complicate the integration of sustainable and digital technologies. While some policies encourage innovation, others may lack the specificity or consistency needed to support technology adoption effectively. Zhang and He (2021) pointed out that in many developing countries, existing construction codes are not adequately updated to accommodate emerging technologies, leading to approval delays and compliance difficulties. This gap between policy and technological advancement poses a considerable obstacle to widespread adoption.

4.9.2 Kruskal-Wallis H Test

To assess the differences in perceptions among the three stakeholder groups, the Kruskal–Wallis H test was applied. This non-parametric test is appropriate for identifying group-based differences when the data does not meet normality assumptions. The test revealed that most of the p-values were greater than 0.05, indicating that there were no statistically significant differences in perception among clients, contractors, and consultants for nine of the ten challenges. However, C9 (Measurement and verification issues) was the exception, with a p-value of 0.033, indicating a statistically significant difference in perception among the groups. This challenge was rated highest by contractors (mean = 4.10), while consultants rated it the lowest (mean = 3.59). This suggests that contractors are more affected by the difficulty of measuring performance metrics in sustainable construction, such as energy savings, material efficiency, or carbon emissions. As highlighted by Rajabi, El-Sayegh and Romdhane (2022), reliable verification tools and frameworks are critical for validating the success of sustainable practices, yet many existing methods remain complex or fragmented.

The overall absence of significant differences for most items suggests a broad agreement among stakeholders about the key challenges impeding the adoption of emerging technologies in the industry. This uniformity is consistent with findings by Klufallah, Ibrahim and Moayedi (2019), who observed a growing consensus in the Malaysian construction sector regarding the barriers to sustainability and digitalization. The consistent rankings across stakeholder groups imply that industry-wide strategies can be developed to tackle these challenges holistically, focusing on cost reduction, regulatory clarity, skills development, and support for emerging technologies.

Table 4.5: Mean and Ranking of Challenges of Adopting Emerging Technologies in the Construction Industry

No.	Challenges	Overall (N=120)			Client (N=41)			Contractor (N=40)			Consultant (N=39)			Chi-square	P-value
		Mean	SD	Rank	Mean	SD	Rank	Mean	SD	Rank	Mean	SD	Rank		
C1	High initial cost	4.37	0.755	1	4.37	0.733	1	4.23	0.800	1	4.51	0.721	1	3.203	0.202
C8	Complexity of sustainability design	4.11	0.756	2	3.98	0.758	8	4.13	0.791	3	4.23	0.742	2	2.420	0.298
C3	Lack of awareness and knowledge	4.10	0.874	3	4.17	0.892	4	4.23	0.862	2	3.90	0.852	5	3.880	0.144
C5	Technological uncertainty	4.08	0.784	4	4.24	0.767	2	3.93	0.859	8	4.08	0.703	4	2.942	0.230
C4	Regulatory and policy barriers	4.08	0.795	5	4.20	0.872	3	3.93	0.859	9	4.13	0.615	3	2.737	0.254
C10	Limited availability of green materials	4.01	0.893	6	4.17	0.892	5	3.97	0.832	6	3.87	0.951	7	2.582	0.275
C2	Limited case studies and support	3.98	0.814	7	4.02	0.880	6	4.05	0.783	5	3.85	0.779	8	1.831	0.400
C7	Infrastructure and logistic challenges	3.93	0.932	8	4.00	0.922	7	3.95	0.986	7	3.85	0.904	9	0.821	0.663
C6	Interoperability issues	3.90	0.911	9	3.95	0.865	9	3.88	1.017	10	3.87	0.864	6	0.138	0.933
C9	Measurement and verification issues	3.87	0.907	10	3.90	0.889	10	4.10	0.871	4	3.59	0.910	10	6.811	0.033*

Note: *. The mean difference is significant at the 0.05 level of significance.

4.10 Spearman's Correlation Test

The correlation matrix includes 20 driver items (D1–D20) measured against 10 challenge items (C1–C10) as shown in Table 4.6. A total of 200 individual correlations were evaluated, out of which many demonstrated statistically significant positive relationships. A double asterisk (**) indicates a correlation significant at the 0.01 level, while a single asterisk (*) indicates significance at the 0.05 level. These indicators confirm a meaningful degree of association between various drivers and barriers.

Several drivers showed strong and consistent positive correlations with nearly all challenge variables, suggesting that certain motivators are closely intertwined with perceived obstacles. For example, D1 (Green certifications and standards) correlated significantly with all ten challenge variables, particularly with C1 (high initial cost, r = 0.385**) and C7 (infrastructure and logistics challenges, r = 0.371**). This suggests that while certifications are a major driver toward adopting sustainable technologies, they are also strongly associated with complex implementation hurdles. According to Zhang and He (2021), many green certification processes involve substantial documentation, process adjustments, and upfront investment, which may explain the perceived burden.

Similarly, D6 (Carbon pricing and emissions trading) and D7 (Corporate social responsibility) each correlated with all ten challenges. For D7, the correlations were particularly strong with C1 (r = 0.428**), C4 (regulatory and policy barriers, r = 0.380**), and C9 (measurement and verification issues, r = 0.437**). This finding implies that organizations driven by CSR agendas are also highly sensitive to the structural and regulatory complexities involved in sustainability transformation. (Maqbool and Amaechi, 2022) emphasized that while CSR improves reputation and stakeholder trust, firms often struggle to align such goals with the technical and bureaucratic requirements of sustainability frameworks.

Other drivers such as D9 (Client and investor expectations) and D10 (Reduction of operational costs) also correlated significantly with all ten challenge variables. Notably, D9 had a strong association with C5 (technological uncertainty, r = 0.462**), highlighting that expectations from investors and clients can amplify the perceived risk of adopting unfamiliar technologies. As Liu et al. (2022) pointed out, client demands for sustainable outcomes can increase pressure on contractors to adopt advanced technologies, sometimes before sufficient knowledge or infrastructure is in place.

Interestingly, D17 (Urbanization and sustainable city planning) and D19 (Health and well-being concerns) were among the drivers with complete (or near-complete) correlations with all challenge items. These drivers represent broader societal shifts that compel the construction industry to evolve, yet their associated correlations with challenges such as C4 (regulatory barriers) and C10 (limited availability of green materials) indicate that the transition remains obstructed by real-world constraints. This supports findings by Klufallah, Ibrahim and Moayedi (2019), who noted that although awareness of urban sustainability is increasing in Malaysia, enabling infrastructure and policy frameworks are still catching up.

It is also important to note that D3 (Market demand) and D13 (Technological integration and smart systems) had the fewest total correlations (6 and 7, respectively). While still statistically significant in select cases, their lower correlation totals suggest that these drivers are less frequently perceived as directly affected by the listed challenges. This may imply that while market demand and system integration are important motivators, they are often viewed independently from the more practical or regulatory obstacles that dominate implementation concerns.

The total correlation frequency per challenge revealed that C5 (technological uncertainty) and C3 (lack of awareness and knowledge) had the highest number of significant relationships with drivers (20 each), followed closely by C4 and C6 (19 each). These results suggest that uncertainty and limited technical understanding are among the most cross-cutting issues affecting driver effectiveness. These findings align with (Prabhakaran, Mahamadu and Mahdjoubi, 2022), who identified inadequate awareness and risk aversion as the most common internal barriers to technological adoption in construction projects.

Table 4.6: Correlation between Drivers and Challenges of using Emerging Technologies in Construction Industry

Drivers \ Challenges	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	Total Correlations
D1	0.385**	0.369**	0.341**	0.245**	0.214*	0.272**	0.371**	0.253**	0.333**	0.194*	10
D2	0.317**	0.229*	0.240**	0.198*	0.272**	0.249**	0.336**	0.361**	-	-	8
D3	-	-	0.215*	0.288**	0.195*	-	0.289**	-	0.278**	0.241**	6
D4	0.237**	0.275**	0.305**	0.378**	0.282**	0.199*	0.278**	-	0.377**	0.354**	9
D5	-	0.268**	0.244**	0.227*	0.336**	0.390**	0.354**	0.220*	0.285**	0.188*	9
D6	0.363**	0.306**	0.281**	0.355**	0.233*	0.210*	0.324**	0.274**	0.414**	0.322**	10
D7	0.428**	0.241**	0.354**	0.380**	0.325**	0.422**	0.384**	0.359**	0.437**	0.261**	10
D8	0.221*	0.244**	0.197*	0.346**	0.201*	0.280**	0.212*	-	0.314**	0.238**	9
D9	0.272**	0.357**	0.356**	0.285**	0.462**	0.273**	0.254**	0.290**	0.248**	0.265**	10
D10	0.398**	0.227*	0.289**	0.389**	0.344**	0.248**	0.440**	0.321**	0.225*	0.203*	10
D11	0.347**	0.265**	0.284**	0.353**	0.262**	0.364**	0.375**	0.316**	0.273**	0.246**	10
D12	0.369**	0.261**	0.234*	0.319**	0.337**	0.412**	0.251**	0.237**	0.245**	0.259**	10
D13	-	0.216**	0.189*	-	0.273**	0.190*	0.206*	0.246**	0.247**	-	7
D14	0.480**	0.285**	0.354**	0.399**	0.395**	0.381**	0.353**	0.389**	0.319**	-	9
D15	0.329**	-	0.249**	0.303**	0.195*	0.240**	0.286**	0.342**	-	-	7
D16	0.234*	0.270**	0.322**	0.394**	0.353**	0.288**	0.308**	-	0.341**	-	8
D17	0.269**	0.270**	0.246**	0.366**	0.186*	0.259**	0.409**	0.217*	0.259**	0.323**	10
D18	0.243**	0.248**	0.238**	0.306**	0.245**	0.231*	0.197*	0.313**	0.254**	0.213*	10
D19	0.295**	0.258**	0.212*	0.267**	0.242**	0.303**	0.234*	0.237**	0.229*	0.200*	10
D20	0.197*	0.195*	0.333**	0.292**	0.191*	0.227*	0.253**	-	0.188*	0.187*	9
Total correlations	17	18	20	19	20	19	20	15	18	15	

Note: **. Correlation is significant at the 0.01 level (2-tailed).

*. Correlation is significant at the 0.05 level (2-tailed).

4.11 Exploratory Factor Analysis

4.11.1 Kaiser-Meyer-Olkin (KMO) Test and Bartlett's Test

Exploratory factor analysis (EFA) was conducted to identify and reduce the underlying structure among the 20 driver variables associated with the adoption of emerging technologies in sustainable construction. This method is essential for condensing a large set of interrelated variables into fewer, interpretable factors, which can explain patterns of correlation and latent dimensions within the dataset. Prior to factor extraction, two statistical tests were used to determine the suitability of the data for factor analysis.

Table 4.7 shows the results of Kaiser-Meyer-Olkin (KMO) and Barlett's Tests. The KMO measure of sampling adequacy returned a value of 0.885, which is considered "meritorious" according to Hair Jr. et al. (2019), indicating that the sample size and correlation patterns among the variables were adequate for reliable factor extraction. In addition, Bartlett's Test of Sphericity yielded a statistically significant result (Approximate Chi-Square = 988.973, df = 190, $p < .001$), confirming that the correlation matrix was not an identity matrix and that there were sufficient inter-variable correlations to justify the use of factor analysis. Hence, these tests provided strong empirical support for proceeding with the factor extraction process.

Table 4.7: Results of KMO and Bartlett's Tests

Parameter	Value
Kaiser-Meyer-Olkin measure of sampling adequacy	0.885
Bartlett's test of sphericity	
Approximate chi-square value	988.973
Degree of freedom	190
Significance	<.001

4.11.2 Factor loading and Variance Explained

Figure 4.1 presents the Scree Plot generated through Principal Component Analysis (PCA) to visualize the eigenvalues of the 20 variables previously identified as drivers of emerging technologies for construction sustainability. PCA was applied to extract latent factors that group these variables according to their shared variance. To enhance interpretability, a Varimax rotation method was employed, which maximizes the variance of squared loadings and simplifies the structure of the extracted components, following the procedure outlined by Carrizosa et al. (2020). From the analysis, four components with eigenvalues greater than 1.0 were retained, conforming to the Kaiser criterion that only components exceeding an eigenvalue of 1 should be considered meaningful for interpretation.

The results are summarized in Table 4.8, which shows that these four components collectively explain 57.38% of the total variance. This percentage satisfies the minimum threshold of 50% recommended for social science research and approaches the 60% benchmark cited by Samuels (2016) as a standard for validating factor analysis outcomes. Each of the 20 driver items recorded a factor loading above 0.40, indicating strong associations with their respective components and affirming the structural reliability of the grouping.

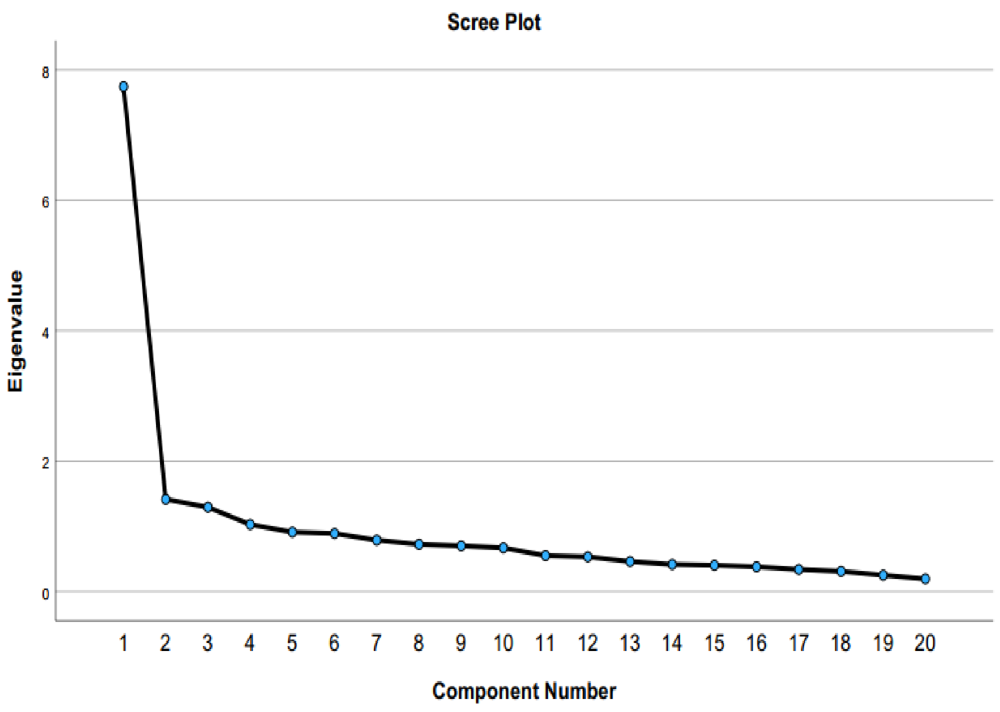

Figure 4.1: Scree Plot for 20 Variables

Table 4.8: Total Variance Explained

Component	Initial eigenvalues		
	Total	Percentage of variance (%)	Cumulative percentage (%)
F1	3.997	19.987	19.987
F2	2.703	13.517	33.504
F3	2.505	12.524	46.028
F4	2.270	11.349	57.377

Table 4.9: Factor Profile for Drivers of Emerging Technologies that Improve Construction Sustainability

Details of Underlying Factors	Factor Loading	Variance Explained (%)
Factor 1: Policy, Innovation and Resource-Based Drivers		
Green certifications and standards	0.746	19.987
Regulatory requirements	0.639	
Innovation in material science	0.617	
Technological integration and smart systems	0.587	
Resource scarcity	0.574	
Urbanization and sustainability city planning	0.545	
Reduction of operational costs	0.485	
Corporate social responsibility (CSR)	0.476	
Factor 2: Environmental and Efficiency Commitments		
Carbon pricing and emissions trading	0.742	13.517
Energy efficiency goals	0.613	
Global environmental initiatives	0.561	
Technological advancement	0.467	
Competitive advantage	0.441	
Factor 3: Market and Stakeholder Influence		
Public and stakeholder pressure	0.792	12.524
Risk management	0.690	
Market demand for sustainable construction	0.531	
Client and investor expectations	0.502	
Factor 4: Human Awareness and Capacity Building		

Educational and training programs	0.795	11.349
Health and well-being concerns	0.677	
Environmental Awareness	0.491	
Cumulative variance explained		57.377

4.11.3 Extraction of Underlying Factor

Factor 1: Policy, Innovation, and Resource-Based Drivers

The first factor accounted for the largest proportion of variance and reflects drivers related to institutional mandates, resource limitations, and innovation. Its composition indicates that the convergence of policy compliance, technological development, and environmental constraints plays a central role in shaping sustainable construction practices. This factor aligns with what Zhang and He (2021) describe as "top-down drivers," where regulations, certifications, and resource-related pressures initiate organizational change.

Notably, this factor represents the strategic positioning of construction firms that respond to a combination of external governance, such as sustainability regulations or urban planning requirements and internal operational priorities like cost-efficiency and CSR. Research by Zhang and Yuan (2023) emphasizes that organizations engaging with policy-driven technologies, such as green rating tools or material innovation systems, are more likely to implement sustainability at scale. The grouping of drivers under this factor illustrates how firms align compliance and innovation to meet both regulatory and market expectations.

Moreover, this factor reflects the influence of urbanization trends and environmental depletion, which push construction stakeholders toward technology-based solutions for smarter infrastructure and optimized resource use (Musarat *et al.*, 2024). Such convergence of institutional, technical, and environmental motives underscores a proactive, strategic response to sustainability challenges, especially within countries undergoing urban expansion and regulatory reform, like Malaysia.

Factor 2: Environmental and Efficiency Commitments

The second factor groups drivers related to global climate goals, energy use, and environmental efficiency. This factor reflects how construction stakeholders align with broader environmental performance objectives, including emissions reduction, energy optimization, and compliance with international environmental frameworks. This grouping supports findings from Labaran et al. (2022) , who noted that construction firms increasingly integrate climate-related initiatives like carbon pricing, energy benchmarking, and environmental certifications as part of their operational strategies. These drivers are often reinforced by global agreements such as the Paris Agreement and national climate policies that incentivize low-carbon technologies.

The presence of competitive advantage within this factor suggests that firms are also motivated by the potential for reputation enhancement and market differentiation through environmental stewardship. According to Saunila et al. (2019), firms that invest in green technologies not only fulfil regulatory requirements but also benefit from increased client trust, investor interest, and long-term cost savings. This factor demonstrates how environmental responsibility and operational efficiency are increasingly interconnected, serving both ecological and economic imperatives.

Factor 3: Market and Stakeholder Influence

The third component represents external pressures from stakeholders, markets, and clients, all of which significantly affect the decision to adopt emerging technologies. This factor suggests that construction organizations are responsive to expectations from the public, investors, and competitive forces. This grouping aligns with Prabhakaran, Mahamadu and Mahdjoubi (2022), who emphasized that stakeholder-driven factors, especially public pressure and client requirements, are increasingly recognized as essential motivators for sustainable construction. In competitive markets, aligning with stakeholder expectations can serve as a form of risk mitigation, brand building, and strategic positioning (Olawumi and Chan, 2018).

Furthermore, this factor indicates a shift in how construction is perceived—not merely as a technical domain but as a service-oriented industry shaped by perception, reputation, and external accountability. According to Gan et al. (2015b), organizations that integrate stakeholder feedback into their sustainability agenda are more adaptable and better positioned to respond to future regulatory or market changes. In essence, this factor highlights how emerging technologies are adopted not only to meet technical goals but to fulfil evolving social and market obligations.

Factor 4: Human Awareness and Capacity Building

The fourth factor reflects the social and human-capital aspects of technology adoption. The inclusion of training programs, environmental awareness, and health-related concerns suggests that effective implementation of sustainable technologies requires both knowledge infrastructure and cultural alignment. This supports findings by Liu, Yi and Wang (2020), who reported that sustainable construction practices are often hindered by a lack of skilled personnel and organizational readiness. Developing technical competence through education and training programs enables firms to overcome barriers related to uncertainty and resistance to change. Musarat et al. (2024) also highlighted the importance of aligning workforce development with sustainability goals, particularly in Southeast Asia, where policy and education are tightly linked.

Additionally, this factor illustrates the growing recognition of employee welfare, safety, and ecological consciousness in shaping technology-related decisions. As noted by Mavi et al. (2021a), internal drivers such as staff empowerment and environmental values can be just as influential as external regulations in advancing sustainability. This component, therefore, underscores the need for organizational strategies that invest in both human development and awareness cultivation as part of a holistic approach to sustainable innovation.

4.12 Comparison among Different Countries

This section offers a thorough overview of the causes of construction disputes in certain nations, including Malaysia, Sri Lanka, China, Europe, Singapore and the United Kingdom. Although each research's specific areas of focus and goals may differ, they enhance the comprehension of the factors faced within various national settings. All this research has been published since 2014.

Table 4.10 presents a comparative overview of key drivers influencing the adoption of emerging technologies for sustainable construction across six countries, based on selected studies. Policy, innovation, and resource-based drivers are the most consistently identified factors, and they are highlighted in all countries except Sri Lanka. Environmental and efficiency commitments appear prominently in Sri Lanka, China and Europe, indicating a growing emphasis on ecological performance. Besides, market and stakeholder influence are also noted in all countries except Singapore, reflecting the impact of demand and external expectations. However, human awareness and capacity building are the least addressed, with only Malaysia and the UK recognising it as a critical driver. This suggests a research gap in exploring the role of education and training in advancing sustainable construction globally.

Table 4.10: Comparison with Previous Studies

Countries	Drivers: Current Study / Authors	Policy, Innovation, and Resource-based Drivers	Environmental and Efficiency Commitments	Market and Stakeholder Influence	Human Awareness and Capacity Building
Malaysia	(Khoshnava *et al.*, 2014)	✓		✓	✓
Sri Lanka	(Weerarathna and Bandara, 2023)		✓	✓	
China	(Zhang and He, 2021)	✓	✓	✓	
Europe	(Kivimaa and Martiskainen, 2018)	✓	✓	✓	
Singapore	(Agyekum, Goodier and Oppon, 2022)	✓			
UK	(Maqbool and Amaechi, 2022)	✓		✓	✓
	Frequency	5	3	5	2

4.13 Summary

This chapter presents the findings from the quantitative research, emphasizing data organization, analysis, and interpretation. The pre-test survey, with full stakeholder participation, validated the questionnaire’s clarity and reliability. The main survey, distributed to 280 construction professionals across Malaysia, achieved a 42.86% response rate, with respondents representing diverse roles, sectors, educational backgrounds, regions, and project types. Most participants possessed basic to moderate familiarity with sustainable construction technologies. Reliability analysis confirmed the internal consistency of the questionnaire items, with Cronbach’s Alpha values indicating good to excellent reliability. Normality tests revealed non-normal data distribution, leading to the use of non-parametric analysis methods such as Kruskal-Wallis and Spearman’s correlation. The analysis of opportunities highlighted the industry's recognition of smart water-saving systems and energy-efficient solutions as key to sustainability, with clients showing the strongest support. Lastly, the factor analysis successfully discovered 4 underlying factors from 20 drivers of emerging technologies that improve sustainability. Overall, the results underscore a positive outlook towards integrating emerging technologies to enhance sustainability in construction, while also identifying challenges and drivers influencing adoption.

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

5.1 Introduction

This chapter consolidates the key findings in relation to the research aim and objectives, summarizing how the applied methods addressed the core questions. It discusses the practical implications for the construction industry, acknowledges the study's limitations, and offers recommendations to guide future research and support the advancement of emerging technologies for sustainable construction.

5.2 Conclusion

The construction industry has long been a critical pillar of economic development, yet it is increasingly under pressure to modernize and improve efficiency through technological innovation. This study set out to explore the integration of sustainable processes within construction projects, with particular emphasis on the role of emerging technologies in driving these changes. The purpose of the study was to examine how modern technological innovations such as Building Information Modelling (BIM), green materials, prefabrication, and renewable energy integration can contribute to more environmentally responsible and efficient construction practices. Through the investigation of current practices and emerging trends, the study aimed to provide a clearer understanding of the opportunities and challenges that lie ahead for the construction industry in embracing sustainability.

The research was driven by the underlying problem that the construction sector remains a major contributor to environmental degradation, including high carbon emissions, material waste, and excessive resource consumption. Despite growing awareness and regulatory pressure, many construction projects still rely heavily on traditional, unsustainable methods. This gap between technological potential and practical application presents a significant obstacle to achieving global sustainability targets. Thus, there was a clear need to investigate how construction stakeholders can adopt innovative tools and processes to address these issues effectively. To accomplish this aim, the study formulated three research objectives which are:

1. To identify the opportunities of emerging technologies on sustainability in the construction industry.
2. To examine the drivers of emerging technologies that improve construction sustainability.
3. To evaluate the challenges of adopting emerging technologies in the construction industry.

The research focused on identifying the opportunities of emerging technologies, the drivers that improve construction sustainability and the challenges of adopting emerging technologies in the construction industry. A detailed literature review had been conducted, 10 opportunities of emerging technologies on sustainability, 20 drivers of emerging technologies that improve sustainability and 10 challenges of adopting emerging technologies were identified. A total response of 120 were collected from the construction practitioners who possess different background through questionnaire survey.

Objective 1:
The evaluation of opportunities associated with emerging technologies in the construction industry highlights a strong consensus among industry stakeholders regarding their potential to enhance sustainability. The analysis, based on responses from 120 participants, showed that the most highly perceived opportunity was the implementation of smart water-saving systems, energy-efficient appliances, and advanced waste management strategies, especially valued by clients due to their operational and environmental benefits. Following closely was the use of digital collaboration platforms like BIM and cloud technologies, highly rated by consultants for their ability to streamline coordination and decision-making, and 3D printing and prefabrication technologies, particularly appreciated by contractors for their precision and waste reduction benefits. Other notable opportunities included digital tools that optimize resource use and minimize rework, and the integration of smart energy management systems and energy-efficient materials. These findings support the

conclusion that emerging technologies are not only feasible but are also widely regarded as essential for driving sustainability in modern construction projects.

Objective 2:

The analysis of drivers influencing the adoption of emerging technologies for sustainability in the construction industry reveals several consistent motivators across stakeholder groups. The most influential driver, rated highest by all professionals, was the reduction of operational costs, highlighting the economic benefits of technologies such as BIM, automation and prefabrication in minimizing waste, labor, and scheduling inefficiencies. Equally ranked were regulatory requirements, reflecting the significant role of government policies like CITP and Industry4WRD in pushing firms toward sustainable practices. Client and investor expectations emerged as another strong driver, underlining the growing importance of aligning construction practices with stakeholder ESG goals. Additionally, the integration of smart systems and digital technologies was recognized for its transformative potential in enhancing productivity and sustainability performance. Lastly, market demand was consistently acknowledged, indicating pressure from industry competition and evolving consumer expectations.

Besides, many statistically significant positive correlations were found in the Spearman's Correlation test, indicating strong links between key motivators such as green certifications (D1), carbon pricing (D6), CSR (D7), and client expectations (D9). Drivers like market demand (D3) and technological integration (D13) showed fewer correlations, suggesting they are less tied to practical obstacles. The most frequently associated challenges were technological uncertainty and lack of awareness, highlighting their widespread impact. These findings underscore the intertwined nature of motivators and obstacles in the adoption of sustainable technologies.

An Exploratory Factor Analysis (EFA) was performed on 20 drivers of emerging technologies in sustainable construction. The data were suitable for analysis, and 4 underlying factors were identified. These factors show that both external (policy, stakeholders) and internal (skills, values) drivers are essential in adopting sustainable technologies.

Objective 3:

The third objective is to identify key challenges hindering the adoption of emerging technologies for sustainable construction. Through mean ranking analysis, the top-ranked challenge was the high initial cost, consistently rated highest by all stakeholder groups. This reflects concerns about the significant capital investment required for implementation new technologies. The second challenge was the complexity of sustainability-oriented design, particularly emphasized by consultants, followed by the lack of awareness and knowledge, which contractors ranked highest. These findings highlight both technical and informational barriers within the industry. Other notable challenges included technological uncertainty and regulatory and policy barriers, indicating apprehensions over evolving technologies and inconsistent regulatory frameworks.

While exploring the interplay between key drivers and challenges in adopting emerging technologies for sustainable construction, a Spearman's rank correlation analysis was performed. High initial cost (C1), lack of awareness and knowledge (C3), technological uncertainty (C5), and regulatory and policy barriers (C4) emerged as the most interconnected challenges, each showing significant correlations with 17–20 driver variables. These results indicate that these four issues are deeply embedded in how stakeholders perceive the feasibility and motivation to adopt emerging technologies. Notably, C3 and C5 had the highest total correlations, suggesting they are the most widespread barriers affecting the influence of multiple drivers. For example, C5 was strongly linked to D9 (client/investor expectations) and D10 (operational cost reduction), reflecting the industry's sensitivity to perceived risks when pressured by performance and financial outcomes. C1 (high initial cost) also correlated significantly with nearly all major drivers, especially D7 (CSR) and D10, highlighting the financial burden even for firms motivated by sustainability. Similarly, C4 (regulatory barriers) showed strong ties to D7, D10, and D14, emphasizing the constraint of unclear or evolving policies. In contrast, C8 (complex design) and C10 (material availability) had fewer total correlations, suggesting they are viewed as more isolated or technical hurdles. Overall, the correlation analysis underscores that the most persistent challenges such as cost, knowledge gaps, uncertainty, and regulation are tightly linked to both external pressures and internal motivators, reinforcing the need for integrated strategies to overcome them.

5.3 Research Implications

This study provides several important implications for both industry practitioners and academic researchers regarding the integration of emerging technologies in sustainable construction. Firstly, the significant correlations between drivers and challenges highlight the need for a more synchronized approach in policy formulation and industry strategy. For instance, while green certifications and corporate social responsibility emerge as strong motivators, they are closely linked with barriers such as high initial costs and regulatory complexities. This suggests that unless enabling frameworks and financial incentives are aligned with these drivers, their impact may be undermined by systemic constraints.

From a practical standpoint, the findings emphasize that technological adoption is not solely a matter of innovation availability but is deeply influenced by organizational readiness, infrastructure support, and stakeholder expectations. The prevalence of challenges such as technological uncertainty and lack of awareness indicates an urgent need for targeted training, capacity-building programs, and stakeholder education to evaluate, adopt, and manage emerging technologies effectively. Industry-academic collaboration can play a vital role in closing this knowledge gap and fostering innovation readiness at multiple organizational levels.

Additionally, the correlation between client and investor expectations with technological barriers reveals a disconnect between stakeholder aspirations and operational capabilities. This indicates the necessity for clearer communication and alignment among developers, contractors, and end-users regarding project feasibility, risk profiles, and performance outcomes. Therefore, construction firms must consider early-stage risk mitigation and knowledge-sharing mechanisms to enhance confidence in adopting unfamiliar technologies.

Academically, this research contributes to the growing body of literature on sustainable construction by empirically validating the interconnectedness between motivation and resistance factors. It underscores the importance of evaluating not just the benefits but also the perceived burdens of technological shifts. Future research should further explore longitudinal changes in these dynamics and assess the effectiveness of emerging policy interventions aimed at overcoming adoption barriers.

5.4 Limitations of research

While this study offers valuable insights into the adoption of emerging technologies in the construction industry, several limitations should be acknowledged. Firstly, the research relied heavily on quantitative methods, particularly survey-based data collection and statistical correlation analyses. Although these methods allowed for broad generalizations and trend identification, they may not fully capture the nuanced perspectives and contextual factors that qualitative approaches such as interviews or case studies could provide.

Secondly, the study was geographically constrained, focusing primarily on a specific region or country (Malaysia). As such, the findings may not be fully generalizable to other regions with different regulatory environments, economic conditions, or technological maturity levels. Construction practices and the pace of technology adoption can vary significantly across countries, which may limit the external validity of the conclusions drawn.

Moreover, the correlation analysis performed in Objective 3 does not establish causation. Although statistically significant relationships between drivers and challenges were identified, it cannot be conclusively determined whether one causes or influences the other. The possibility of confounding variables or indirect effects remains a limitation, especially in a complex, multi-stakeholder industry such as construction. The reliance on self-reported data also introduces the potential for response bias. Participants may have over- or under-reported their perceptions due to social desirability, organizational loyalty, or limited understanding of the technological issues surveyed.

Additionally, while the sample size was adequate for statistical testing, broader sampling across different roles such as policy-makers, end-users, contractors, and suppliers could have provided a more comprehensive understanding of the ecosystem.

Finally, emerging technologies are rapidly evolving by nature. As such, the drivers, challenges, and perceptions identified in this study may change over time, potentially affecting the long-term applicability of the findings. Future research may benefit from longitudinal studies or real-time data to better capture the dynamic nature of technological adoption in construction.

5.5 Recommendations for research

The findings of this study have highlighted several critical insights into the adoption of emerging technologies within the construction industry, particularly in the context of sustainable development. However, as the construction sector continues to evolve alongside rapid technological advancements, further research is essential to deepen understanding and support effective implementation strategies.

Given the evolving nature of emerging technologies in the construction sector, current research should continue to focus on empirical validation of the drivers and challenges identified in this study. In particular, more attention should be devoted to understanding how specific barriers such as high initial costs, technological uncertainty, and regulatory complexities interact with motivators like green certifications, corporate social responsibility, and client expectations. Quantitative studies employing larger sample sizes and multi-country comparisons are recommended to verify the generalizability of findings across different socio-economic and regulatory environments. In addition, longitudinal studies are needed to track how perceptions of challenges and drivers shift as technologies mature and market conditions evolve. Collaborations between academic institutions, industry stakeholders, and policy bodies can also foster more holistic insights by integrating practical constraints with theoretical frameworks.

On the other hand, future studies should consider longitudinal analyses to track the dynamic interactions between drivers and challenges over time. This would offer valuable insights into how policy changes, technological maturity, and market readiness influence adoption trends in different construction contexts. In particular, temporal data could clarify how perceived barriers such as high initial costs or regulatory complexity evolve as technologies become more mainstream.

Second, while this research focused on general industry-wide patterns, there is a need for more sector-specific investigations. Future research should explore technology adoption within sub-sectors such as residential, commercial, infrastructure, and industrial construction, as each may face unique challenges and opportunities. Comparative studies across regions or countries with varying levels of technological readiness and policy frameworks would also help identify contextual best practices.

Third, the role of organizational culture, leadership, and workforce readiness was not deeply examined in this study. Future research could benefit from integrating behavioural and organizational theories to assess how internal management practices, employee training, and change resistance affect technology integration. A mixed-methods approach involving qualitative case studies would be particularly valuable for exploring these softer dimensions of technological transformation.

Furthermore, the emergence of novel digital tools such as digital twins, AI-powered decision systems, and blockchain presents promising yet underexplored avenues. Future research should assess the real-world applicability, scalability, and integration challenges of these technologies, particularly in low- and middle-income countries where resource constraints are more pronounced.

Finally, given the strong association between sustainability drivers and implementation challenges, future research should focus on developing actionable frameworks or decision-support models that balance environmental goals with economic and regulatory feasibility. Collaborative efforts involving academia, industry practitioners, and policymakers will be vital in translating technological potential into widespread, impactful adoption.

5.6 Summary

Overall, this chapter synthesizes the research findings on the adoption of emerging technologies within the construction industry, emphasizing key drivers, prevailing challenges, and their interrelationships. It underscores the significance of technological innovation for sustainable development while acknowledging the systemic barriers that hinder widespread implementation. The insights offered serve as a foundation for both practical improvements in industry practices and the direction of future academic inquiry.

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APPENDICES

Appendix A: Questionnaires

A STUDY ON EXPLORING SUSTAINABLE PROCESSES IN CONSTRUCTION PROJECTS: EMERGING TECHNOLOGIES AND OPPORTUNITIES

Dear respondents,

My name is Lee Win Nie, a final year undergraduate student of Bachelor of Science (Honours) Quantity Surveying from Universiti Tunku Abdul Rahman (UTAR), Sungai Long Campus. I am currently carrying out research on "Exploring Sustainable Processes in Construction Projects: Emerging Technologies and Opportunities". This questionnaire is designed with the purpose of collecting data or information related to the aforementioned research topic.

This questionnaire consists of **Four (4) Sections**, which may require not more than 10 minutes to complete. Kindly provide your responses and answer all the questions to the best of your knowledge. There is no incorrect answer to any of these statements. Please be noted that all responses will be treated confidentially. The data and information collected will only be used for academic purposes in data collection. If you do not wish to participate, you may quit the survey at any time.

For any inquiries about the survey, please feel free to contact me at 019-2559843 or email me at leewnie22@1utar.my. Your participation in this survey is greatly appreciated and will assist me in conducting my research.

Thank you for your valuable time dedicated to completing this questionnaire!

Your faithfully,

Lee Win Nie

A STUDY ON EXPLORING SUSTAINABLE PROCESSES IN CONSTRUCTION PROJECTS: EMERGING TECHNOLOGIES AND OPPORTUNITIES

Section A: Demographic Background

1. What is your role in construction projects?
    - o Client
    - o Contractor
    - o Consultant
    - o Other…
2. What is your background in construction industry?
    - o Architect
    - o C&S Engineer
    - o M&E Engineer
    - o Quantity Surveyor
    - o Project/Construction Management
    - o Other…
3. Which type of organization are you affiliated with?
    - o Public Sector
    - o Private Sector
    - o Other…
4. How many years of experience do you have in construction industry?
    - o Less than 5 years
    - o 5 to 10 years
    - o 11 to 20 years
    - o More than 20 years
5. What is your highest level of education?
    - o Primary/Secondary Education
    - o Diploma
    - o Degree
    - o Postgraduate Degree (Master and PhD)
    - o Other…

6. In which region(s) do you primarily operate? (Select all that apply)
    - ☐ Klang Valley (Selangor, Putrajaya and KL)
    - ☐ Northern Region (Perlis, Kedah, Penang, Perak)
    - ☐ Southern Region (Johor, Melaka, Negeri Sembilan)
    - ☐ East Coast (Kelantan, Terengganu, Pahang)
    - ☐ Sabah
    - ☐ Sarawak
    - ☐ Other…
7. What types of construction projects are you primarily involved in? (Select all that apply)
    - ☐ Residential project
    - ☐ Commercial project
    - ☐ Industrial project
    - ☐ Infrastructure (e.g., roads, bridges)
    - ☐ Environmental (e.g., sustainable projects)
    - ☐ Other…
8. Which statement best describes your experience with sustainable construction technologies?
    - ☐ I am unfamiliar with these technologies.
    - ☐ I have heard of these technologies but haven’t used them.
    - ☐ I have basic experience using these technologies.
    - ☐ I am proficient in using d implementing these technologies.
    - ☐ I am an expert and actively incorporate these technologies in projects.

Section B: Emerging Technologies and Opportunities

1. Enhanced Collaboration and Efficiency

Scenario: Imagine a construction project where all team members, from architects to builders, can access real-time project updates and share changes instantly using digital platforms like BIM or cloud technology.

	Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree
How likely do you think using digital platforms would improve collaboration and efficiency in construction projects?	1	2	3	4	5

2. Reduction of Material Waste

Scenario: Suppose a construction company uses advanced technology like 3D printing or prefabrication to produce only the exact materials needed, reducing the amount of excess material on site.

	Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree
How effective do you think technologies like 3D printing and prefabrication are in reducing material waste in construction projects?	1	2	3	4	5

3. Improved Energy Efficiency

Scenario: Imagine a building project that uses smart energy management systems and energy-efficient building materials to reduce electricity use throughout the building's lifecycle.

	Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree
To what extend do you believe that smart energy systems and energy-efficient materials can improve the energy efficiency of construction projects?	1	2	3	4	5

4. Reduction in Construction Timelines

Scenario: Picture a construction site where drones are used for surveying, robotics for repetitive tasks and prefabricated parts are delivered ready to install, which shortens the overall construction time.

	Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree
How much do you think the use of technologies like drones, robotics and prefabrication can reduce construction timelines?	1	2	3	4	5

5. Resource Efficiency

Scenario: Imagine a project that utilizes smart water-saving systems, energy-efficient appliances and advanced waste management strategies to minimize the use of water, energy and raw materials.

	Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree
How effective do you think resource-saving technologies are in improving resource efficiency on construction sites?	1	2	3	4	5

6. Enhanced Energy Resilience

Scenario: Picture a new development that integrates hybrid renewable energy systems (like solar and wind) along with energy storage to ensure continuous power, even during power outages.

	Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree
How beneficial do you think renewable energy systems and energy storage technologies are in enhancing the energy resilience of construction projects?	1	2	3	4	5

7. Carbon Footprint Reduction

Scenario: Suppose a company incorporates carbon capture technology and low-emission materials to actively reduce the amount of carbon produced during construction.

	Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree
Suppose a company incorporates carbon capture and low-emission materials can help reduce the carbon footprint of construction projects?	1	2	3	4	5

8. Improved Safety

Scenario: Imagine a construction site where workers wear smart PPE (Personal Protective Equipment) that alerts them to potential hazards, while drones and robotics handle risky tasks.

	Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree
How much do you agree that technologies like smart PPE, drones and robotics can improve safety on construction sites?	1	2	3	4	5

9. Cost Savings and Economic Benefits

Scenario: Consider a project where digital tools optimize resource use, reduce waste and minimize rework, ultimately lowering overall costs and improving project profitability.

	Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree
How likely do you think digital and resource-saving technologies are to create cost savings and economic benefits in construction?	1	2	3	4	5

10. Supporting Circular Economy Principles

Scenario: Imagine a building that is designed for easy disassembly, with materials that can be reused or recycled after the building's lifecycle, reducing waste and supporting a circular economy.

	Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree
How effective do you think construction methods that promote material reuse and recycling are in supporting circular economy principles?	1	2	3	4	5

Section C: Drivers of Using Emerging Technologies

Under **regulatory and market influences**, please indicate how much they influence your organization's sustainability efforts.

	No Influence	Little Influence	Moderate Influence	Strong Influence	Very Strongly Influence
Green certifications and standards	1	2	3	4	5
Regulatory requirements (e.g., local building codes, environmental laws)	1	2	3	4	5
Market demand for sustainable construction	1	2	3	4	5
Public and stakeholder pressure	1	2	3	4	5
Global environmental initiatives	1	2	3	4	5
Carbon pricing and emissions trading	1	2	3	4	5

Under **corporate and organizational factors**, please indicate how much the following factors influence your organization's sustainability initiatives.

	No Influence	Little Influence	Moderate Influence	Strong Influence	Very Strongly Influence
Corporate Social Responsibility (CSR)	1	2	3	4	5
Risk management	1	2	3	4	5
Client and investor expectations	1	2	3	4	5
Reduction of operational costs	1	2	3	4	5

Under **technological and innovation approach**, please indicate how much the following factors influence your organization's adoption of sustainable technologies.

	No Influence	Little Influence	Moderate Influence	Strong Influence	Very Strongly Influence
Technological advancement (e.g., robotics, AI, 3D printing)	1	2	3	4	5
Innovation in material science (e.g., advanced sustainable materials, composites)	1	2	3	4	5
Technological integration and smart systems (e.g., BIM, digital twins, IoT)	1	2	3	4	5
Reduction of operational costs	1	2	3	4	5

Under **resource and environmental considerations**, please indicate how much the following considerations influence your organization's sustainability initiatives.

	No Influence	Little Influence	Moderate Influence	Strong Influence	Very Strongly Influence
Resource scarcity (e.g., depletion of natural resources)	1	2	3	4	5
Energy efficiency goals (e.g., reduced energy consumption)	1	2	3	4	5
Environmental awareness (e.g., efforts to mitigate environmental harm)	1	2	3	4	5
Urbanization and sustainable city planning (e.g., green urban design)	1	2	3	4	5

Under **competitive and strategic motivations**, please indicate how much the following motivations influence your organization's sustainability practices.

	No Influence	Little Influence	Moderate Influence	Strong Influence	Very Strongly Influence
Competitive advantage	1	2	3	4	5
Health and well-being concerns	1	2	3	4	5
Educational and training programs	1	2	3	4	5

Section D: Challenges of Using Emerging Technology

To what extend do the following challenges affect your organization's adoption of emerging technologies for sustainability in construction?

	Not a Challenge	Minor Challenge	Moderate Challenge	Major Challenge	Critical Challenge
High initial cost	1	2	3	4	5
Limited case studies and support	1	2	3	4	5
Lack of awareness and knowledge	1	2	3	4	5
Regulatory and policy barriers	1	2	3	4	5
Technological uncertainty	1	2	3	4	5
Interoperability issues	1	2	3	4	5
Infrastructure and logistic challenges	1	2	3	4	5
Complexity of sustainable design	1	2	3	4	5
Measurement and verification issues	1	2	3	4	5
Limited availability of green materials	1	2	3	4	5