FROM BLUEPRINT TO GREENPRINT: SMART TECHNOLOGIES POWERING SUSTAINABLE CONSTRUCTION IN MALAYSIA

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Abstract

This study investigates the role of smart technologies in supporting sustainability management within Malaysian construction projects and identifies the key drivers influencing their adoption among primary stakeholders. Addressing a research gap in how digital innovations are prioritised and implemented for sustainability, the study collected 101 valid responses representing clients, consultants, and contractors. Descriptive statistical analysis using mean scores identified Building Information Modelling (BIM), Additive Manufacturing, and the Internet of Things (IoT) as the top-ranked technologies. The consensus across stakeholder groups highlights a shared recognition of these technologies' significance. Key adoption drivers include cost reduction, process optimisation, and increased stakeholder awareness. This study is timely, given the urgent need for the construction industry to adopt green practices in tandem with digital transformation, ensuring it remains competitive with other sectors. The findings offer valuable insights for practitioners and policymakers to strategically advance smart sustainable practices, aligning environmental goals with digital innovation. The study contributes incremental knowledge to Malaysian construction and offers broader implications for contexts seeking to integrate smart technologies in pursuit of a more sustainable and efficient future.

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1.0 INTRODUCTION

Sustainability has become a central concern across various sectors, including the construction industry, which is well known for its significant environmental, social, and economic impacts. Broadly defined, sustainability refers to the capacity to maintain development over time in a way that meets present needs without compromising the ability of future generations to meet theirs (Mollenkamp 2025). In support of this vision, the United Nations introduced the Sustainable Development Goals (SDGs) to encourage practices that harmonise economic development with environmental protection and social equity (Fei *et al.* 2021).

The construction industry is a major driver of global economic activity, valued at approximately USD 1.7 trillion and contributing between 5 to 7 per cent of global Gross Domestic Product (GDP) (Alaloul *et al.* 2021). In Malaysia, the sector continues to play a pivotal economic role. In the second quarter of 2024, strong construction activity supported a 5.9 per cent year-on-year GDP expansion (CIDB Malaysia 2024). This upward trend continued into the first quarter of 2025, where the construction sector recorded a remarkable 14.2 per cent growth, contributing significantly to Malaysia's overall GDP growth of 4.4 per cent (Malaysian Ministry of Finance 2025). This robust performance reflects sustained infrastructure development and aligns with the government's MADANI framework, which promotes high-quality investments and pro-development policies. Importantly, the framework also underscores the need for sustainable economic growth, positioning the construction sector as a key player in advancing green construction practices and supporting national commitments to environmental stewardship and climate resilience.

In line with Malaysia's push towards digital transformation, the Construction 4.0 Strategic Plan (2021–2025) by CIDB Malaysia provides a national roadmap for modernising the industry through the adoption of emerging technologies (CIDB 2020). This includes the transition from automated production to a greater level of digitalisation, with the integration of cyber-physical systems (CPS) that connect physical construction processes with digital intelligence. These technologies are revolutionising traditional construction by enabling real-time data exchange, autonomous operations, and advanced analytics, thus driving a new era of modernisation for humanity. Such transformation supports modernisation efforts by enhancing productivity and driving sustainable, data-driven construction outcomes (Forcael *et al.* 2020; Lekan *et al.* 2021). Despite its vital economic contribution and technological progress, the construction industry faces growing scrutiny due to its significant environmental impact. It is a major source of greenhouse gas emissions, consumes large volumes of natural resources, and generates substantial construction and demolition waste (Yap *et al.* 2024a).

To address these challenges, sustainable construction has gained prominence. Sustainable construction involves the application of environmentally responsible and resource-efficient processes throughout a building's lifecycle, from design to deconstruction (Kibert 2022). This concept is grounded in the "triple bottom line" framework, which emphasises balancing economic viability, environmental responsibility, and social equity (Nogueira *et al.* 2025). Thus, sustainability encompasses not only reducing environmental harm but also promoting cost efficiency and social inclusivity in project development.

More recently, the convergence of sustainability and technological advancement has introduced a new dimension: smart sustainable practices. These involve integrating digital technologies - such as Building Information Modelling (BIM), the Internet of Things (IoT), artificial intelligence, and advanced data analytics - to improve sustainability performance in construction projects. Smart sustainable practices enable real-time monitoring and resource optimisation, helping reduce environmental impacts and improve project efficiency and outcomes (Mohamed *et al.* 2024).

Within Malaysia, initiatives like the Green Building Index (GBI), the promotion of Industrialised Building Systems (IBS), and strategic plans by the Construction Industry Development Board (CIDB) reflect a growing institutional commitment to sustainability. Although the Construction Industry Transformation Programme (CITP) 2016 to 2020 laid a strong foundation in areas such as environmental sustainability and productivity, it has since concluded. The latest strategic direction under CIDB's Construction Strategic Plan 2021 to 2025 continues to emphasise sustainability, with a greater focus on environmental resilience, digital integration, and green construction practices aligned with national development goals. However, the utilisation of smart technologies to support sustainable development remains uneven and underexplored locally. While many technologies are available, their adoption and integration into sustainability frameworks still lack consistency, industry-wide coordination, and comprehensive documentation.

Current research often addresses sustainability initiatives or technological innovation separately, missing the opportunity to explore their combined benefits (Chan *et al.* 2019; Olawumi and Chan 2020). Furthermore, much of the literature is international, with limited focus on Malaysia's unique policy environment, industry practices, and contextual factors. The lack of localised insight limits stakeholders in formulating effective strategies to promote smart sustainable practices.

Achieving sustainability goals in construction requires more than simply having advanced technologies. It depends fundamentally on the enabling conditions that drive their adoption, such as institutional support, regulatory frameworks, organisational capacity, and stakeholder engagement (Saka *et al.* 2020; Ferdosi *et al.* 2023). These drivers influence how effectively digital innovations contribute to environmental performance, operational efficiency, and long-term project sustainability. As Malaysia pursues a green and digital future through frameworks such as the MADANI economic narrative, the Construction 4.0 Strategic Plan (CIDB 2020), and the Construction Industry Transformation Programme (CITP) (CIDB 2015), the integration of smart technologies becomes essential to achieving strategic national and government-aligned sustainability objectives.

However, the adoption of smart sustainable technologies is often hindered by contextual barriers such as high upfront costs, limited digital literacy, fragmented project delivery systems, and resistance to change (Durdyev *et al.* 2018; Oke *et al.* 2021; Ogunsanya *et al.* 2022). These constraints can weaken or delay adoption efforts, especially when enabling conditions are unclear or misaligned. Therefore, identifying and strengthening the right set of adoption drivers is crucial to overcoming these challenges and accelerating the uptake of smart sustainability practices.

Given these considerations, this study aims to explore the types of smart sustainable practices that have the potential to support sustainability management within the Malaysian construction industry and to identify the key drivers encouraging their adoption. By examining these technologies and the underlying motivators, the research seeks to contribute to the advancement of smart sustainability in construction, providing valuable insights for industry practitioners, policymakers, and researchers striving to align Malaysia's construction activities with national and global sustainability objectives. This study addresses two primary research questions:

1. What smart technologies can potentially support sustainability management in Malaysian construction projects?
2. What are the key drivers encouraging the adoption of these smart sustainable practices?

2.0 LITERATURE REVIEW

2.1 Triple Bottom Line and Sustainability

Sustainable Development (SD) is commonly framed through the Triple Bottom Line (TBL) concept, which encompasses three pillars: economic, social, and environmental sustainability (Khan *et al.* 2021; Nogueira *et al.* 2025). These pillars correspond to profit (traditional financial performance), people (social responsibility), and planet (environmental stewardship). For true sustainability, these dimensions must progress in harmony, as all three are essential (Evans *et al.* 2017).

Economically, smart technologies offer benefits such as reduced labour and material costs, increased productivity and flexibility, shortened setup times, and improved customer satisfaction (Witkowski 2017; Dalenogare *et al.* 2018). Environmentally, digital tools enable energy optimisation, waste reduction, and carbon footprint tracking, while facilitating product reuse, recycling, and remanufacturing (Bai *et al.* 2020). Socially, technologies like wearables enhance worker health and safety, while automating repetitive tasks to improve job satisfaction (Bai *et al.* 2020).

The United Nations' 2030 Agenda for Sustainable Development, embodied in the 17 Sustainable Development Goals (SDGs), further supports the TBL framework by addressing economic growth, social equity, and environmental protection globally. These goals set concrete targets - such as reducing poverty, ensuring health, education, and gender equality - that construction industries can align with to contribute meaningfully to sustainable development worldwide.

2.2 Definition of Smart Sustainability

Smart sustainability refers to the application of technologies aimed at enhancing sustainability across multiple dimensions, including energy management, material utilisation, waste reduction, cost savings, and the health and well-being of communities. As shown in Table 1, sustainability encompasses not only environmental factors but also economic and social aspects by creating economic opportunities and fostering resilient societies. Simply put, smart sustainability integrates the concepts of 'smart' and 'sustainable' within the construction industry to enable more digitalised and environmentally friendly construction methods. The use of technology in construction seeks to improve economic performance, minimise the environmental impacts associated with traditional construction processes, and deliver benefits to local communities and their surroundings. In light of this, smart sustainability serves as a strategic conduit for integrating sustainability goals with advanced digital technologies. The rapid advancement of transformative technologies - such as artificial intelligence (AI), machine learning (ML), data analytics, and the Internet of Things (IoT - collectively known as exponential technologies, offers significant potential to accelerate progress toward achieving the SDGs (Pan and Nishant 2023). Table 1 summarises various definitions of smart sustainability as proposed by different authors.

Table 1: Definition of smart sustainability

No.	Definition of Smart Sustainability	References
1	"The organisational activities that seek to advance the sustainable development goals through creative deployment of technologies that create, use, transmit, or source electronic data."	(George *et al.* 2021, p. 1000)
2	"Developing so-called high technologies for implementation in various areas of economic activity allow us to apply the principles of sustainable development in an intelligent manner"	(Radziejowska & Sobotka 2021, p.1)
3	Introducing technologies into the processes to improve economic gains and to minimise the environmental impact in delivering construction products and services.	(Prebanić & Vukomanović 2021)
4	"Developing smart grids and putting in place smart and green technologies are given high priority across Europe, in order to reduce carbon emissions, achieve future goals of sustainability, and assure electric stability to cities and their citizens."	(Biresselioglu *et al.* 2018, p. 418)

2.3 Smart Sustainable Practices in Construction Industry

The construction industry is currently experiencing and adapting to the changes brought about by the Fourth Industrial Revolution. This revolution has led to the adoption of new technologies, from which the construction industry has also benefited. The term Construction 4.0, first introduced by Roland Berger, encompasses digitalisation in construction processes. It incorporates four key concepts: digital data, digital access to data, improved connectivity, and automation of machines (Forcael *et al.* 2020). Construction 4.0 further consists of a framework of three main components: the integration of digitalised technologies, industrial manufacturing and construction, and a cybersecurity system (Sawhney *et al.* 2020).

Table 2: Literature map for smart sustainable practices in construction industry

		References																
Ref	**Smart sustainable practices**	**(Forcael et al.**	**(Sacks et al. 2018)**	**(Craveiro et al.**	**(Osunsanmi et al.**	**(Lekan et al. 2021)**	**(Kor et al. 2023)**	**Tahmasebinia et**	**(Turner et al. 2021)**	**(Liu et al. 2022)**	**(Wangler et al.**	**(Li et al. 2019)**	**(Wang et al. 2020)**	**(Arowoiya et al. 2020)**	**(Li et al. 2018)**	**(Qureshi et al. 2020)**	**(Shojaei et al. 2020)**	**Total**
P1	Building information modelling	√	√	√	√	√	√		√				√		√	√		10
P2	Additive manufacture / 3D printing	√		√	√	√		√		√	√							7
P3	Internet of things (IoT)	√					√		√				√	√	√	√		7
P4	Sensors			√					√				√	√	√			5
P5	Augmented reality (AR) / virtual reality (VR)	√			√	√										√		4
P6	Artificial intelligence / machine learning	√					√							√		√		4
P7	Cloud computing				√	√										√		3
P8	Global positioning system					√							√		√			3
P9	Big Data	√			√													2
P10	Blockchain											√					√	2
P11	Robotics			√			√											2
P12	Automation			√														1

Industrial production and construction under this framework include 3D printing, additive manufacturing, prefabrication, automation, and other off-site construction methods that reduce on-site labor. These processes often integrate with Building Information Modelling (BIM), enabling construction professionals to transmit digital instructions for physical production. In terms of cyber-physical systems, automation technologies - such as actuators, sensors, and the Internet of Things (IoT) - are deployed to transform digital signals into physical actions across production, transport, and assembly stages.

Furthermore, digital technologies critical to Construction 4.0 include laser scanning, blockchain, big data and analytics, augmented reality (AR), and artificial intelligence (AI). A key enabler for these technologies is the Digital Ecosystem, which refers to interconnected IT resources functioning collectively as a unified system (Brush 2023). These innovations provide construction companies with opportunities to enhance quality and competitiveness.

Table 2 presents a literature map summarising various smart sustainable practices identified in the construction industry. According to the literature, BIM and IoT are among the most frequently adopted technologies to support sustainability goals and enable data-driven decision-making (Forcael *et al.* 2020). Other practices such as 3D printing, sensors, AR/VR, AI/ML, and cloud computing also contribute significantly to the smart and sustainable transformation of the sector.

2.4 Key Drivers for Smart Sustainable Practices to be used in Construction Industry

The construction industry is under increasing pressure to adopt smarter and more sustainable approaches in response to environmental degradation, rising operational costs, and evolving stakeholder expectations. Within this context, numerous studies have investigated the factors that drive the implementation of smart sustainable practices in construction. A prominent and widely acknowledged driver is the potential to reduce construction costs. Researchers such as Opoku *et al.* (2022), Badamasi *et al.* (2022), and Won *et al.* (2022) have highlighted cost savings as a key motivation for adopting smart technologies, as these tools can help streamline processes, minimise material waste, and improve resource utilisation. These economic advantages are particularly relevant in developing countries like Malaysia, where cost efficiency remains a central concern for both public and private sector projects.

Table 3 presents a comprehensive literature map summarising the key drivers that influence the adoption of smart sustainable practices in the construction industry. According to this table, the most frequently cited driver is the potential for reduced construction costs, referenced by eight different sources. This indicates strong scholarly consensus on the economic benefits of smart technologies.

In addition to cost reduction, the optimisation of construction processes has emerged as another important driver. Technologies such as Building Information Modelling (BIM), Internet of Things (IoT), and data analytics are increasingly being used to improve project scheduling, workflow coordination, and supply chain efficiency. Authors such as Khan *et al.* (2021) and Olanrewaju *et al.* (2022) argue that these smart solutions help mitigate common industry challenges such as delays, rework, and coordination failures. Through enhanced integration of planning and execution stages, smart practices allow stakeholders to gain greater control over project delivery, contributing to improved overall performance. This driver is also strongly supported in Table 3, appearing in seven of the reviewed studies.

Improved health and safety is another consistently identified incentive for the adoption of smart sustainable practices. The construction sector is inherently high-risk, with frequent incidents related to site hazards, equipment misuse, and human error. Smart systems such as real-time monitoring devices, wearable sensors, and predictive safety analytics have shown promise in reducing accidents and enhancing worker wellbeing. Studies by Saka *et al.* (2020) and Yap *et al.* (2022), emphasise that incorporating safety-focused technologies not only supports regulatory compliance but also builds a safer working environment, which can translate into long-term cost and reputation benefits for firms. As shown in Table 3, this driver was also highlighted in seven publications.

Stakeholder awareness has further been recognised as a fundamental driver. Raising awareness among clients, consultants, and contractors about the benefits and practicalities of smart sustainable practices is essential to overcoming resistance to change. The works of Olawumi and Chan (2020) and Yap *et al.* (2023) stress the importance of education, training, and industry dialogue in promoting a more forward-thinking mind-set. When stakeholders are well-informed about the value and applicability of these innovations, they are more likely to advocate for their use and embed them into standard practice. This driver is reflected in five sources in Table 3.

Financial capacity is another critical factor influencing adoption. While smart technologies can deliver long-term returns, the initial investment can be substantial. Saka *et al.* (2020) and Yap *et al.* (2024) argue that the availability of financial resources determines whether firms are willing and able to invest in new systems. This financial preparedness is often linked to company size, client support, and access to funding schemes. Hence, financial incentives, subsidies, or targeted support from government and industry bodies may serve as catalysts for wider adoption. Table 3 also supports this point, showing “Adequate financial resources” cited in four studies.

Additional drivers such as enhanced energy management, higher productivity, and improved decision-making are also gaining traction in the literature. Energy management, in particular, is essential in meeting carbon reduction goals and complying with green certification requirements. Improved data availability and analytics allow decision-makers to assess performance metrics in real time, enabling more responsive and sustainable project management. Although some drivers - such as top management support, which appears in only one source in Table 3 - are less frequently cited, they remain crucial to ensure strategic alignment and organisational commitment.

In summary, Table 3 illustrates a diverse and interconnected set of drivers - ranging from cost and productivity gains to awareness, funding, and environmental concerns - that collectively shape the adoption of smart sustainable practices in the construction industry. Understanding these drivers is essential for stakeholders aiming to accelerate the digital and sustainable transformation of the sector.

2.5 Gaps of Knowledge

Although sustainability and technological advancement have become central themes in global construction discourse, their integration within the Malaysian construction industry remains limited and underexplored. While policies and initiatives such as the Green Building Index and the Construction Industry Transformation Programme demonstrate a growing commitment to sustainable development, the adoption of digital innovations that enhance sustainability outcomes - such as Building Information Modelling, the Internet of Things and artificial intelligence - remains inconsistent. Existing studies often examine sustainability and smart technologies separately, overlooking their combined impact and potential to improve project performance.

This gap is particularly significant given the increasing environmental pressures, resource constraints and rising demands for social equity within the construction sector. The industry must reduce its ecological footprint while meeting expectations for cost-effective and inclusive development. Smart sustainable practices that use digital technologies to optimise resources, reduce waste and support data-driven decision making offer a promising way to meet these challenges. However, empirical research on how these practices are currently applied, especially in the Malaysian context, is scarce. Furthermore, little is known about the key factors motivating primary stakeholders - clients, consultants and contractors - to adopt such innovations. Addressing these gaps is essential to fostering a more sustainable and technologically advanced construction industry in Malaysia.

3.0 RESEARCH METHODOLOGY

This study adopts a pragmatic research paradigm, which is well-suited for addressing complex real-world issues by focusing on solutions that work in practice (Creswell and Clark 2011). Pragmatism supports methodological flexibility and emphasises the practical consequences of research, making it particularly relevant to applied fields such as construction management, where the integration of sustainability and technology demands both theoretical insight and practical implementation (Sherratt *et al.* 2025). A quantitative research approach was employed to examine current trends in smart sustainable practices and to identify the key drivers influencing their adoption. This approach aligns with prior research, including Olawumi and Chan (2020), who investigated the drivers of smart sustainable practices in Hong Kong, Yap *et al.* (2024b), who examined the benefits of sustainable procurement in the Malaysian construction industry and Darko *et al.* (2018), who explored factors influencing the adoption of green building technologies in Ghana. The pragmatic orientation of the study facilitates flexible methodological choices aimed at bridging the gap between theory and practice, particularly within the context of sustainable construction development.

The research process commenced with an extensive review of the literature to conceptualise smart sustainable practices and to identify potential drivers for their adoption. This review guided the development of a structured questionnaire, which was designed to collect empirical data from key industry stakeholders - namely clients, consultants, and contractors - across various organisations in Malaysia. The questionnaire consisted of Likert-scale items aimed at gauging respondents' perceptions of the relevance and importance of identified practices and drivers.

Table 3: Literature map for drivers to smart sustainable practices in construction industry

		References														
Ref	**Drivers**	**(Opoku et al. 2022)**	**(Badamasi et al. 2022)**	**(Saka et al. 2020)**	**(Windapo 2014)**	**(Won et al. 2022)**	**(Häkkinen and Belloni 2011)**	**(Khan et al. 2022)**	**(Olanrewaju et al. 2022)**	**(Chan 2014)**	**(Kivits and Furneaux 2013)**	**(Olawumi and Chan 2020)**	**(Antón and Díaz 2014)**	**(Eadie et al. 2013)**	**(Olsson et al. 2019)**	**Total**
D1	Reduced construction costs	√	√	√		√		√					√	√	√	8
D2	Optimised construction process	√	√					√	√	√	√			√		7
D3	Improved health and safety	√	√		√	√				√				√	√	7
D4	High awareness of stakeholders			√	√		√					√	√			5
D5	Adequate financial resources			√			√				√				√	4
D6	Enhanced energy management	√						√			√		√			4
D7	Higher productivity			√				√	√							3
D8	Enhanced decision making	√							√							2
D9	Reduced time for overall design process	√												√		2
D10	Improved environmental monitoring	√							√							2
D11	Sustainable data management					√				√						2
D12	Top management support			√												1

The collected data were analysed using the Statistical Package for the Social Sciences (SPSS). Mean scores were calculated to prioritise both the smart sustainable practices currently observed and the key drivers facilitating their adoption. Higher mean values indicate stronger agreement or perceived importance among respondents (Olawumi and Chan 2020). To determine whether statistically significant differences exist in the perceptions among different respondent groups (clients, consultants, and contractors), the Kruskal-Wallis (KW) test was applied. This non-parametric method is suitable for comparing three or more independent groups and does not assume a normal distribution (Yap *et al.* 2024b), making it appropriate for ordinal data derived from Likert-scale responses.

This methodological approach enables a comprehensive understanding of the prioritised smart sustainable practices and the key factors driving their adoption within the construction industry. It also provides insights into variations in stakeholder perspectives, offering a nuanced view of industry readiness and alignment with sustainability goals in the Malaysian context.

3.1 Questionnaire Development

The questionnaire was structured into three distinct parts to facilitate a clear and comprehensive data collection process. The survey began with an introductory section that clearly explained the research objectives, ensuring that participants understood the purpose of the study. The first section gathered demographic information from respondents, including their role within the company, the nature of their construction-related business, years of professional experience, and highest level of educational attainment.

The second section sought respondents' views on the contribution of various technologies to sustainability management in construction. Participants rated each technology using a five-point scale ranging from "not at all significant" (1) to "extremely significant" (5). The final section concentrated on identifying key drivers encouraging the adoption of smart sustainable practices within the construction industry. Respondents evaluated twelve identified drivers using a five-point Likert scale, where 1 indicated the driver was perceived as "ineffective" and 5 as "very effective".

To confirm the questionnaire's clarity and reliability, a pilot test was conducted involving five participants representing key stakeholder groups: two main contractors, two consultants, and one developer. Feedback from this pilot was instrumental in refining the survey, leading to corrections in grammar, improved wording, and the removal of ambiguous items. Responses collected during this pre-test phase were not included in the main analysis.

3.2 Sampling and Data Collection

The research targeted construction industry stakeholders in Malaysia's Klang Valley, a key urban hub centred on Kuala Lumpur and known for its concentration of construction activities (Yasin *et al.* 2022). The focus was on construction professionals as the primary unit of analysis. To gather participants, a combination of convenience and snowball sampling techniques was used. Convenience sampling allowed the recruitment of readily available respondents, while snowball sampling helped to broaden the participant pool by encouraging referrals within professional networks until no new information was obtained.

In total, 320 electronic questionnaires were disseminated through various digital platforms, including email, LinkedIn, and WhatsApp. To maximise participation, reminders were sent over a four-week period following the initial distribution. This method was intended to capture a diverse and representative sample, supporting the collection of robust and generalisable data for the study.

4.0 RESULTS AND DISCUSSION

4.1 Survey Participants and Demographics

Over a four-week period, 101 valid responses were obtained (see Table 4), resulting in a 31.68% response rate, which is acceptable for construction management research. The sample included 27 clients (26.7%), 34 consultants (33.7%), and 40 contractors (39.6%), ensuring balanced representation across key stakeholder groups. Nearly 60% of respondents had over ten years of industry experience, offering seasoned perspectives on construction practices.

In terms of roles, the majority were junior (59.4%) and senior executives (28.7%), with nearly 12% holding managerial and above positions. Academically, more than 70% had at least a bachelor's degree, including 8.9% with postgraduate qualifications. This mix of practical experience and academic background strengthens the credibility of insights regarding the adoption of smart sustainable practices in Malaysia's construction sector.

4.2 Prioritising Smart Technologies for Sustainability Management in Construction

Cronbach's alpha for the twelve assessed smart technologies was 0.821, exceeding the accepted threshold of 0.70 and confirming the internal consistency and reliability of the measurement scale (Olawumi and Chan 2020; Yap *et al.* 2024b). Mean scores and standard deviations were calculated based on responses to a five-point Likert scale evaluating the perceived importance of each smart technology in supporting sustainability management in the construction industry. Table 5 presents the results, ranked by mean score. In cases where two or more technologies shared the same mean, the technology with the lower standard deviation was prioritised, indicating greater consensus among respondents.

All twelve technologies achieved mean scores above 3.00, signalling general agreement on their relevance to sustainable construction practices. Building Information Modelling (BIM) (Mean = 4.94) and Additive Manufacturing/3D Printing (Mean = 4.90) emerged as the highest-rated technologies, reflecting widespread recognition of their transformative potential. They were followed by the Internet of Things (IoT) (Mean = 4.66), Sensors and Augmented/Virtual Reality (both Mean = 4.43), and Artificial Intelligence/Machine Learning (AI/ML) (Mean = 4.39), forming a top tier of perceived high-impact technologies.

The remaining technologies - Robotics, Automation, Cloud Computing, Big Data, GPS, and Blockchain - ranked lower but still scored between 3.10 and 4.01, indicating their acknowledged relevance in advancing digital integration and sustainability in construction, albeit with relatively lesser influence.

Analysis by stakeholder group (developers, consultants, and contractors) showed overall agreement on the top five smart sustainable technologies: BIM, Additive Manufacturing, IoT, Sensors, and Augmented Reality/AI. However, contractors uniquely ranked Additive Manufacturing as the most significant, ahead of BIM, whereas consultants placed AI above Augmented Reality, contrasting with the preferences of developers and contractors.

Referring to Table 5, BIM is identified as the most impactful practice for sustainability in construction overall, with both developers and consultants concurring on its top ranking. This aligns with prior research highlighting BIM's role in enhancing economic, social, and environmental sustainability. For instance, Lekan *et al.* (2021) emphasise BIM's capacity to increase productivity and enable an integrative approach supporting social sustainability, while Govindan *et al.* (2016) highlight BIM's contributions to time and cost efficiency aligned with sustainability objectives. Contractors, however, ranked Additive Manufacturing higher than BIM, likely due to less exposure to BIM software compared to developers and consultants. El-Sayegh *et al.* (2020) reported contractors' particular interest in on-site 3D printing applications, and Thurairajah and Goucher (2013) discussed BIM's benefits from cost consultants' perspectives, including clash detection and enhanced information sharing. Thus, BIM's advantages appear more directly realised by developers and consultants.

Sensors and Augmented Reality shared identical mean scores and standard deviations overall, indicating equal perceived contribution to sustainability following IoT. However, subtle differences exist among stakeholder groups: developers view Augmented Reality as slightly more impactful, contractors favour Sensors, and consultants rate Sensors on par with AI (Table 5).

Table 4: Respondent's demographic profile

Parameters	Categories	Respondents Group			Total	Frequency (%)
		Client	Consultant	Contractor		
Working experience	< 5 years	12	10	15	37	36.63
	6-10 years	8	15	14	37	36.63
	11- 15 years	4	5	8	17	16.83
	16-20 years	1	3	2	6	5.94
	> 20 years	2	1	1	4	3.96
Position	Junior Executive	19	21	20	60	59.41
	Senior Executive	5	8	16	29	28.71
	Manager	2	4	3	9	8.91
	Senior Manager	1	1	1	3	2.97
	Top Management	0	0	0	0	0
Academic Qualification	SPM / High School	0	0	0	0	0
	Diploma	9	12	7	28	27.72
	Bachelor's Degree	16	19	29	64	63.37
	Postgraduate Degree	2	3	4	9	8.91

Table 5: Mean and ranking of smart sustainable practices

Ref	Smart sustainable practices	Overall (N=101)			Client (N=27)			Consultant (N=33)			Contractors (N=41)			Chisquare	Asymptotic significance
		Mean	S.D	Rank	Mean	S.D	Rank	Mean	S.D	Rank	Mean	S.D	Rank		
P1	Building information modelling	4.9406	0.2765	1	4.9630	0.1925	1	4.9697	0.1741	1	4.9024	0.3745	2	0.860	0.650
P2	Additive manufacturing/ 3D printing	4.9010	0.3002	2	4.9259	0.2669	2	4.8788	0.3314	2	4.9024	0.3004	1	0.368	0.832
P3	Internet of things (IoT)	4.6634	0.5706	3	4.6667	0.5547	3	4.7273	0.4523	3	4.6098	0.6663	3	0.286	0.867
P4	Sensors	4.4257	0.5540	4	4.4074	0.5724	5	4.3939	0.4962	4	4.4634	0.5957	4	0.580	0.748
P5	Augmented reality (AR)/ virtual reality (VR)	4.4257	0.5540	4	4.5556	0.5064	4	4.3333	0.4787	6	4.4146	0.6315	5	2.683	0.262
P6	Artificial intelligence/ machine learning	4.3861	0.5093	6	4.3704	0.5649	6	4.3939	0.4962	4	4.3902	0.4939	6	0.005	0.998
P11	Robotics	4.0099	0.4358	7	3.9630	0.4369	8	4.0909	0.3844	7	3.9756	0.4737	7	1.699	0.428
P12	Automation	3.9901	0.4582	8	4.0000	0.4804	7	4.0303	0.4667	8	3.9512	0.4448	8	0.560	0.756
P7	Cloud computing	3.7030	0.6090	9	3.6667	0.5547	9	3.6970	0.5855	9	3.7317	0.6717	9	0.218	0.897
P9	Big data	3.3069	0.5957	10	3.3333	0.6202	10	3.3030	0.5855	10	3.2927	0.6018	10	0.396	0.821
P8	Global positioning system	3.1980	0.5481	11	3.1852	0.5573	11	3.2424	0.6139	11	3.1707	0.4951	11	0.170	0.919
P10	Blockchain	3.0990	0.5001	12	2.9630	0.5175	12	3.1515	0.5075	12	3.1463	0.4775	12	4.939	0.085

Interestingly, automation and robotics, initially ranked lower, are now regarded more favourably by respondents, at 7th and 8th positions respectively. Pan and Zhang (2021) note that construction automation and robotics (CAR) are gaining global recognition as critical to the industry's sustainable future and have developed methods to assess CAR's sustainability impact. Nonetheless, Urrea and Kern (2025) caution that current robotics technologies still face challenges in precision and error correction, indicating ongoing development needs. Respondents' elevated ranking of robotics and automation suggests growing industry acknowledgement of their potential to enhance sustainability outcomes. Conversely, blockchain technology was consistently rated lowest (12th), perceived as having the least direct contribution to sustainability in construction.

The Kruskal–Wallis test was applied to assess differences in technology perceptions across stakeholder groups. The results indicated no statistically significant differences ($p > 0.05$) among developers, consultants, and contractors, suggesting a consistent and homogeneous understanding of the importance of these smart technologies for sustainability management. This consensus reinforces the robustness of the findings and indicates a shared recognition within the Malaysian construction industry of the critical role digital tools play in driving sustainable practices.

4.3 Prioritising the Key Drivers of Smart Sustainable Practices

As part of the analysis, Cronbach's alpha for the twelve evaluated drivers was recorded at 0.815, exceeding the accepted threshold of 0.70 and confirming the internal consistency and reliability of the scale (Olawumi and Chan 2020; Yap *et al.* 2024b). Mean scores and standard deviations (SD) were computed to prioritise the drivers, as presented in Table 5. All drivers achieved mean scores above 3.00, indicating general agreement among respondents regarding their importance in advancing smart sustainable practices within the Malaysian construction sector.

The results as presented in Table 6 reveal that the 1st ranked driver was *reduced construction costs* (Mean = 4.87), reflecting industry consensus that financial efficiency is a core motivator for smart sustainability adoption. According to Ogunbiyi and Goulding (2013) and Yap *et al.* (2024b), sustainable construction enhances cost savings while fostering innovation and competitiveness. Khan *et al.* (2022) highlighted that Modular Integrated Construction (MIC) can lead to cost savings of up to 20% through offsite manufacturing, while also reducing the likelihood of cost escalation across project phases. Furthermore, smart technologies reduce dependency on manual labour, lowering operational costs. As Shi *et al.* (2013) emphasised, cost-effectiveness should be considered from a lifecycle perspective rather than focusing solely on initial capital investment. Thus, the ability to reduce overall construction costs emerges as a compelling driver for the implementation of smart sustainable practices.

The 2nd ranked driver was *optimised construction processes* (Mean = 4.79), underscoring the perceived value of improved workflow efficiency. Langston and Zhang (2021) noted that methods such as prefabrication and lean construction contribute significantly to productivity and streamline operations from the early design phase. Efficient construction processes help shorten project timelines, thereby reducing total costs and supporting the traditional project management triangle of time, cost, and quality. For example, the use of Building Information Modelling (BIM) facilitates 4D visualisation of construction sequencing, enabling stakeholders to detect and resolve design clashes early, thereby reducing rework (Akponeware and Adamu 2017; Yap *et al.* 2022a).

The 3rd ranked driver was *improved health and safety* (Mean = 4.75), reaffirming the industry's emphasis on worker well-being and social sustainability. This finding aligns with Durdyev *et al.* (2018), who placed health and safety among the top social drivers of sustainable construction. Smart technologies such as Augmented Reality (AR) and Virtual Reality (VR) can enhance on-site hazard identification and simulation training, as discussed by Li *et al.* (2018), thereby reducing accident rates and fostering a safer working environment.

Table 6: Mean and ranking to drivers of implementation

Ref	Drivers	Overall (N=101)			Client (N=27)			Consultant (N=33)			Contractors (N=41)			Chisquare	Asymptotic significance
		Mean	S.D	Rank	Mean	S.D	Rank	Mean	S.D	Rank	Mean	S.D	Rank		
D1	Reduced construction costs	4.8713	0.4618	1	4.9630	0.1925	1	4.8485	0.6185	1	4.8293	0.4417	1	2.672	0.263
D2	Optimised construction process	4.7921	0.4542	2	4.8519	0.3620	3	4.7273	0.5168	2	4.8049	0.4593	2	1.039	0.595
D3	Improved health and safety	4.7525	0.5551	3	4.8889	0.3026	2	4.7273	0.6742	3	4.6829	0.5674	3	2.618	0.270
D4	High awareness of stakeholders	4.4653	0.5963	4	4.4444	0.5064	4	4.6061	0.6586	4	4.3659	0.5812	4	4.773	0.092
D5	Adequate financial resources	4.3960	0.6013	5	4.4444	0.5037	5	4.3939	0.7882	5	4.3659	0.4877	5	0.823	0.663
D7	Higher productivity	4.2079	0.4758	6	4.2222	0.5064	6	4.3030	0.4667	6	4.1220	0.4580	6	2.553	0.279
D6	Enhanced energy management	4.1386	0.5662	7	4.1481	0.5338	7	4.1818	0.6826	7	4.0976	0.4902	7	0.930	0.628
D8	Enhanced decision making	4.1287	0.4830	8	4.1852	0.4833	8	4.1212	0.4846	8	4.0976	0.4902	8	0.428	0.807
D9	Reduced time for overall design process	3.9109	0.5495	9	4.0000	0.3922	9	3.9697	0.5855	9	3.8049	0.6008	11	2.798	0.247
D10	Improved environmental monitoring	3.8812	0.5155	10	4.0000	0.4804	10	3.8485	0.5658	10	3.8293	0.4951	9	2.002	0.367
D12	Top management support	3.8400	0.6624	11	3.8889	0.5774	11	3.8125	0.8206	11	3.8293	0.5875	10	0.417	0.812
D11	Sustainable data management	3.7228	0.5851	12	3.7778	0.6405	12	3.7273	0.5741	12	3.6829	0.5674	12	0.713	0.700

The 4th ranked driver was *high awareness of stakeholders* (Mean = 4.47). Stakeholder awareness is critical in driving the demand and support for smart sustainable practices. Oke *et al.* (2021) similarly ranked advocacy and awareness as key enablers for the adoption of sustainable construction. Olawumi *et al.* (2018) further stressed the importance of stakeholder knowledge and engagement in shaping project outcomes. With improved awareness, stakeholders are more likely to endorse and invest in smart and sustainable solutions.

The 5th ranked driver was *adequate financial resources* (Mean = 4.40), which highlights the foundational role of economic capacity in enabling the adoption of smart practices. Financial limitations are widely acknowledged as a barrier to sustainability implementation. Therefore, when adequate funding is available - particularly from clients - organisations are more willing to commit to sustainable technologies and strategies. Despite the potentially high initial investment in tools such as BIM and automation, these are offset by long-term cost savings, aligning with the benefits highlighted in the 1st ranked driver.

Lower-ranked drivers included *sustainable data management* (Mean = 3.72), *top management support* (Mean = 3.84), and *improved environmental monitoring* (Mean = 3.88). While still viewed positively, these were perceived to exert less influence relative to the top-ranked drivers.

Additionally, the Kruskal–Wallis test indicated no statistically significant differences in perceptions among the three stakeholder groups ($p > 0.05$), confirming consistent views across developers, consultants, and contractors. This alignment reinforces the robustness of the findings and highlights a unified industry perspective on the enablers of smart sustainable practices in the Malaysian construction context.

5.0 CONCLUSION

This study has provided valuable insights into the adoption of smart technologies that support sustainability management within the Malaysian construction industry. The findings reveal a clear prioritisation of key technologies, namely Building Information Modelling (BIM), Additive Manufacturing, and the Internet of Things (IoT), which are widely recognised by primary stakeholders as pivotal enablers of sustainable construction practices. Moreover, the consensus observed among clients, consultants, and contractors underscores a unified industry perspective on the importance of these technologies and the critical key drivers influencing their adoption, including cost reduction, process optimisation, and stakeholder awareness. Figure 1 presents the top three findings from this study, applying the Pareto principle (also known as the 80/20 rule).

This principle proposes that a small number of key factors are often responsible for the majority of outcomes. In this case, BIM, Additive Manufacturing, and IoT, together with their associated key drivers, are identified as contributing to approximately 80 per cent of the impact on smart sustainability adoption in the Malaysian construction industry.

The application of the Pareto principle is particularly important as it enables stakeholders to focus their efforts and resources on the most influential technologies and key drivers. Rather than dispersing attention across a wide range of lower impact factors, this targeted approach allows for more effective strategic planning, decision making, and policy development. Prioritising high impact areas also supports stronger alignment with national sustainability objectives and facilitates a more efficient and scalable transition towards environmentally responsible and resilient construction practices. This strategic focus contributes to sustainability outcomes that reflect a balanced advancement of economic efficiency, environmental responsibility, and social well-being, driven by the effective adoption of smart technologies in the construction industry.

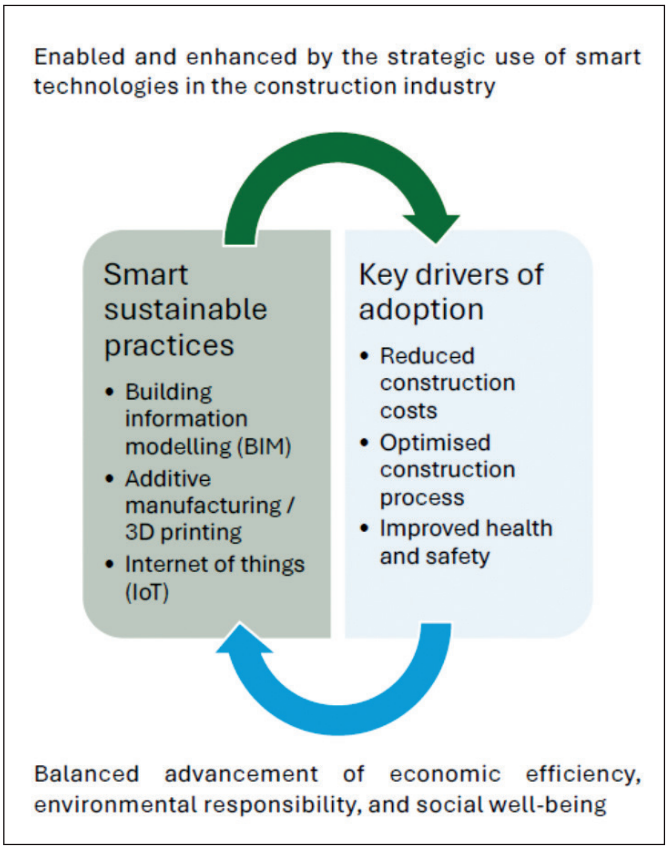

Figure 1: Priority technologies and adoption drivers in the Malaysian construction industry based on the Pareto principle

These results not only contribute incremental theoretical knowledge by contextualising smart sustainable practices within the Malaysian setting but also offer practical implications for industry practitioners and policymakers. By aligning digital transformation efforts with sustainability goals, the construction industry can accelerate its progress towards greener and more efficient project delivery. Encouraging the strategic adoption of these smart technologies can facilitate improved environmental performance, enhanced social well-being, and economic growth, thereby reinforcing the industry's commitment to sustainable development.

In an era where digital innovation is rapidly reshaping industries globally, the construction industry cannot afford to lag behind. This study highlights the timely imperative for embracing smart sustainable technologies as integral components of Malaysia's broader digital transformation agenda, ultimately supporting the transition to a greener and more resilient future.

6.0 RECOMMENDATIONS FOR THE MALAYSIAN CONSTRUCTION FRATERNITY

In alignment with the findings of this study and the strategic priorities outlined by the Construction Industry Development Board (CIDB) and national agendas such as the MADANI Framework - which emphasises sustainability and digital transformation as fundamental pillars for Malaysia's future development - the following recommendations are proposed to accelerate the adoption of smart sustainable practices within the Malaysian construction industry:

i) Accelerate Adoption of Smart Technologies to Drive Sustainability

Prioritise the implementation of leading smart technologies - Building Information Modelling (BIM), Additive Manufacturing, and the Internet of Things (IoT) - to strengthen sustainability management in construction projects. These technologies facilitate improved resource optimisation, waste reduction, and enhanced environmental outcomes.

ii) Leverage Key Adoption Drivers to Facilitate Digital Transformation

Focus on critical drivers identified in this study, such as cost reduction, process optimisation, and heightened stakeholder awareness, to foster broader acceptance of smart sustainable practices. Tailored training programmes and awareness campaigns are essential to address resistance and bridge skill gaps.

iii) Align Industry Practices with National Sustainability and Digitalisation Agendas

Ensure integration of industry efforts with Malaysia's MADANI Framework and initiatives including the Construction 4.0 Strategic Plan and National Construction Policy (NCP 2030) to advance a greener, more efficient construction sector. This alignment will promote policy coherence and unlock governmental support.

iv) Enhance Collaborative Engagement Across Stakeholders

Encourage strong collaboration among developers, consultants, contractors, and policymakers to secure shared understanding and commitment to sustainability objectives. Inclusive engagement fosters knowledge exchange and facilitates smooth adoption of new technologies.

v) Invest in Capacity Building and Continuous Innovation

Develop comprehensive, industry-wide programmes to upskill the workforce with emerging technologies and sustainable construction practices. Supporting ongoing innovation and research will sustain Malaysia's competitiveness and underpin the transition towards a digital and sustainable construction future.

6.1 Limitations and Future Research

This study offers valuable insights into the prioritisation and adoption drivers of smart sustainable technologies within the Malaysian construction industry. However, the findings are based on responses from 101 participants representing primary stakeholder groups, which may limit the generalisability across the wider construction industry, particularly among smaller firms or peripheral actors. Future research could expand the sample size and include a broader range of stakeholders such as subcontractors, suppliers, and regulatory authorities to provide a more comprehensive perspective.

While the study identifies key drivers and prioritised technologies, it does not explore the barriers that may impede their practical adoption. Common challenges include the high upfront cost of implementation, especially for SMEs; limited digital literacy and skills shortages among the existing workforce; resistance to organisational change, often due to cultural inertia or fear of redundancy; and regulatory gaps or absence of supportive policy frameworks that hinder innovation uptake. These barriers can significantly slow down digital transformation despite recognised sustainability benefits.

Further qualitative or mixed method studies are recommended to explore these contextual obstacles in depth, which would provide a more grounded understanding of the implementation landscape. In addition, the cross-sectional nature of the data captures perceptions at one point in time. Longitudinal research could track how the prioritisation of smart technologies and adoption drivers evolve over time as sustainability mandates and digitalisation mature. Finally, since this research is specific to Malaysia, comparative studies with other countries would be valuable in examining how differing socioeconomic, cultural, or regulatory environments shape the adoption of smart sustainable practices in construction. Addressing these limitations will strengthen both the theoretical framework and practical application of smart technology adoption for sustainability management. ■

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AUTHORS' CONTRIBUTIONS

Jeffrey Boon Hui Yap	Conceptualisation, study design, supervision, and writing – original draft.
Jeng Min Lim	Data collection, methodology, and formal analysis.
Ooi Kuan Tan	Writing – review and editing, and data interpretation.
Wun She Yap	Data validation, visualisation, and project resources.
Chee Fui Wong	Technical support, administration/project coordination, and investigation.

REFERENCES

[1] Akponeware, A. O., & Adamu, Z. A. (2017). Clash detection or clash avoidance? An investigation into coordination problems in 3D BIM. *Buildings, 7*(3), 75.

[2] Alaloul, W. S., Musarat, M. A., Rabbani, M. B. A., Iqbal, Q., Maqsoom, A., & Farooq, W. (2021). Construction sector contribution to economic stability: Malaysian GDP distribution. *Sustainability, 13*(9), 5012.

[3] Antón, L. Á., & Díaz, J. (2014). Integration of LCA and BIM for sustainable construction. *International Journal of Social, Education, Economics and Management Engineering, 8*(5), 1356–1360.

[4] Arowoiya, V. A., Oke, A. E., Aigbavboa, C. O., & Aliu, J. (2020). An appraisal of the adoption of Internet of Things (IoT) elements for sustainable construction. *Journal of Engineering, Design and Technology, 18*(5), 1193–1208.

[5] Badamasi, A. A., Aryal, K. R., Makarfi, U. U., & Dodo, M. (2022). Drivers and barriers of virtual reality adoption in the UK AEC industry. *Engineering, Construction and Architectural Management, 29*(3), 1307–1318.

[6] Bai, C., Dallasega, P., Orzes, G., & Sarkis, J. (2020). Industry 4.0 technologies assessment: A sustainability perspective. *International Journal of Production Economics, 229*, 107776.

[7] Biresselioglu, M. E., Nilsen, M., Demir, M. H., Røyrvik, J., & Koksvik, G. (2018). Examining the barriers and motivators affecting European decision-makers in the development of smart and green energy technologies. *Journal of Cleaner Production, 198*, 417–429.

[8] Brush, K. (2019). What is a digital ecosystem? *TechTarget*. https://www.techtarget.com/searchcio/definition/digital-ecosystem

[9] Chan, C. T. W. (2014). Barriers of implementing BIM in construction industry from the designers' perspective: A Hong Kong experience. *Journal of System and Management Sciences, 4*(2), 24–40.

[10] Chan, D. W. M., Olawumi, T. O., & Ho, A. M. L. (2019). Critical success factors for building information modelling (BIM) implementation in Hong Kong. *Engineering, Construction and Architectural Management, 26*(9), 1838–1854.

[11] Construction Industry Development Board (CIDB). (2020). *Construction 4.0 strategic plan (2021–2025)*. Kuala Lumpur, Malaysia.

[12] Construction Industry Development Board (CIDB). (2015). *Construction industry transformation programme (2016–2020)*. Kuala Lumpur, Malaysia.

[13] CIDB Malaysia. (2024). *Key construction projects to drive GDP in second half of 2024*. https://www.cidb.gov.my/eng/key-construction-projects-to-drive-gdp-in-second-half-of-2024/

[14] Craveiro, F., Duarte, J. P., Bartolo, H., & Bartolo, P. J. (2019). Additive manufacturing as an enabling technology for digital construction: A perspective on Construction 4.0. *Automation in Construction, 103*(July), 251–267.

[15] Creswell, J. W. L., & Clark, V. L. P. (2011). *Designing and conducting mixed methods research* (2nd ed.). Thousand Oaks, CA: Sage Publications, Inc.

[16] Dalenogare, L. S., Benitez, G. B., Ayala, N. F., & Frank, A. G. (2018). The expected contribution of Industry 4.0 technologies for industrial performance. *International Journal of Production Economics, 204*(October), 383–394.

[17] Darko, A., Chan, A. P. C., Yang, Y., Shan, M., He, B. J., & Gou, Z. (2018). Influences of barriers, drivers, and promotion strategies on green building technologies adoption in developing countries: The Ghanaian case. *Journal of Cleaner Production, 200*(November), 687–703.

[18] Durdyev, S., Zavadskas, E. K., Thurnell, D., Banaitis, A., & Ihtiyar, A. (2018). Sustainable construction industry in Cambodia: Awareness, drivers and barriers. *Sustainability, 10*(2), 392.

[19] Eadie, R., Odeyinka, H., Browne, M., McKeown, C., & Yohanis, M. (2013). An analysis of the drivers for adopting building information modelling. *Journal of Information Technology in Construction, 18*(17), 338–352.

[20] El-Sayegh, S., Romdhane, L., & Manjikian, S. (2020). A critical review of 3D printing in construction: Benefits, challenges, and risks. *Archives of Civil and Mechanical Engineering, 20*(34), 1–25.

[21] Evans, S., Vladimirova, D., Holgado, M., Van Fossen, K., Yang, M., Silva, E. A., & Barlow, C. Y. (2017). Business model innovation for sustainability: Towards a unified perspective for creation of sustainable business models. *Business Strategy and the Environment, 26*(5), 597–608.

[22] Fei, W., Opoku, A., Agyekum, K., Oppon, J. A., Ahmed, V., Chen, C., & Lok, K. L. (2021). The critical role of the construction industry in achieving the sustainable development goals (SDGs): Delivering projects for the common good. *Sustainability, 13*(16), 9112.

[23] Ferdosi, H., Abbasianjahromi, H., Banihashemi, S., & Ravanshadnia, M. (2023). BIM applications in sustainable construction: Scientometric and state-of-the-art review. *International Journal of Construction Management, 23*(12), 1969–1981.

[24] Forcael, E., Ferrari, I., & Opazo-Vega, A. (2020). Construction 4.0: A literature review. *Sustainability, 12*(22), 9755.

[25] George, G., Merrill, R. K., & Schillebeeckx, S. J. D. (2021). Digital sustainability and entrepreneurship: How digital innovations are helping tackle climate change and sustainable development. *Entrepreneurship: Theory and Practice, 45*(5), 999–1027.

[26] Govindan, K., Shankar, K. M., & Kannan, D. (2016). Sustainable material selection for the construction industry: A hybrid multi-criteria decision-making approach. *Renewable and Sustainable Energy Reviews, 55*(March), 1274–1288.

[27] Häkkinen, T., & Belloni, K. (2011). Barriers and drivers for sustainable building. *Building Research and Information, 39*(3), 239–255.

[28] Khan, A., Yu, R., Liu, T., Guan, H., & Oh, E. (2022). Drivers towards adopting modular integrated construction for affordable sustainable housing: A total interpretive structural modelling (TISM) method. *Buildings, 12*(5), 637.

[29] Khan, I. S., Ahmad, M. O., & Majava, J. (2021). Industry 4.0 and sustainable development: A systematic mapping of triple bottom line, circular economy and sustainable business models perspectives. *Journal of Cleaner Production, 297*(May), 126655.

[30] Kibert, C. J. (2022). *Sustainable construction: Green building design and delivery* (5th ed.). Hoboken, NJ: John Wiley.

[31] Kivits, R. A., & Furneaux, C. (2013). BIM: Enabling sustainability and asset management through knowledge management. *The Scientific World Journal, 2013*, 983721.

[32] Kor, M., Yitmen, I., & Alizadehsalehi, S. (2023). An investigation for integration of deep learning and digital twins towards Construction 4.0. *Smart and Sustainable Built Environment, 12*(3), 461–487.

[33] Langston, C., & Zhang, W. (2021). DfMA: Towards an integrated strategy for a more productive and sustainable construction industry in Australia. *Sustainability (Switzerland), 13*(16), 9219.

[34] Lekan, A., Clinton, A., & James, O. (2021). The disruptive adaptations of Construction 4.0 and Industry 4.0 as a pathway to sustainable innovation and inclusive industrial technological development. *Buildings, 11*(3), 79.

[35] Li, J., Greenwood, D., & Kassem, M. (2019). Blockchain in the built environment and construction industry: A systematic review, conceptual models, and practical use cases. *Automation in Construction, 102*(June), 288–307.

[36] Li, X., Yi, W., Chi, H. L., Wang, X., & Chan, A. P. C. (2018). A critical review of virtual and augmented reality (VR/AR) applications in construction safety. *Automation in Construction, 86*(February), 150–162.

[37] Liu, Q., Trevisan, A. H., Yang, M., & Mascarenhas, J. (2022). A framework of digital technologies for the circular economy: Digital functions and mechanisms. *Business Strategy and the Environment, 31*(5), 2171–2192.

[38] Malaysian Ministry of Finance. (2025). *4.4% GDP growth in first quarter 2025 fortifies Malaysia's fundamentals in the face of global uncertainties*. https://www.mof.gov.my/portal/en/news/press-release/4-4-gdp-growth-in-first-quarter-2025-fortifies-malaysias-fundamentals-in-the-face-of-global-uncertainties

[39] Mohamed, A. M. O., Mohamed, D., Fayad, A., & Al Nahyan, M. T. (2024). Enhancing decision making and decarbonation in environmental management: A review on the role of digital technologies. *Sustainability, 16*(16), 7156.

[40] Mollenkamp, D. T. (2025). *What is sustainability? How sustainabilities work, benefits, and examples*. https://www.investopedia.com/terms/s/sustainability.asp

[41] Nogueira, E., Gomes, S., & Lopes, J. M. (2025). Unveiling triple bottom line's influence on business performance. *Discover Sustainability, 6*(43), 1–18.*https://doi.org/10.1007/s43621-025-00804-x

[42] Ogunbiyi, O., & Goulding, J. (2013). A review of lean concept and its application to sustainable construction in the UK. *International Journal of Sustainable Construction Engineering & Technology, 4*(2), 82–92.

[43] Ogunsanya, O. A., Aigbavboa, C. O., Thwala, D. W., & Edwards, D. J. (2022). Barriers to sustainable procurement in the Nigerian construction industry: An exploratory factor analysis. *International Journal of Construction Management, 22*(5), 861–872.* https://doi.org/10.1080/15623599.2019.1658697

[44] Oke, A. E., Kineber, A. F., Albukhari, I., Othman, I., & Kingsley, C. (2021). Assessment of cloud computing success factors for sustainable construction industry: The case of Nigeria. *Buildings, 11*(2), 36.

[45] Olanrewaju, O. I., Kineber, A. F., Chileshe, N., & Edwards, D. J. (2022). Modelling the relationship between Building Information Modelling (BIM) implementation barriers, usage, and awareness on building project lifecycle. *Building and Environment, 207*(January), 108556. https://doi.org/10.1016/j.buildenv.2021.108556

[46] Olawumi, T. O., & Chan, D. W. M. (2020). Key drivers for smart and sustainable practices in the built environment. *Engineering, Construction and Architectural Management, 27*(6), 1257–1281.

[47] Olawumi, T. O., Chan, D. W. M., Wong, J. K. W., & Chan, A. P. C. (2018). Barriers to the integration of BIM and sustainability practices in construction projects: A Delphi survey of international experts. *Journal of Building Engineering, 20*(November), 60–71.

[48] Olsson, N. O. E., Shafqat, A., Arica, E., & Økland, A. (2019). 3D-printing technology in construction: Results from a survey. *Emerald Reach Proceedings Series, 2*, 349–356.

[49] Opoku, D. G. J., Perera, S., Osei-Kyei, R., Rashidi, M., Famakinwa, T., & Bamdad, K. (2022). Drivers for digital twin adoption in the construction industry: A systematic literature review. *Buildings, 12*(2), 113.

[50] Osunsanmi, T., Aigbavboa, C., Oke, A., & Ohiomah, I. (2018). Construction 4.0: Its impact towards delivering quality and sustainable houses in South Africa. In *Creative Construction Conference 2018 – Proceedings* (pp. 147–156). Budapest University of Technology and Economics.

[51] Pan, S. L., & Nishant, R. (2023). Artificial intelligence for digital sustainability: An insight into domain-specific research and future directions. *International Journal of Information Management, 72*(October), 102668.

[52] Pan, Y., & Zhang, L. (2021). Roles of artificial intelligence in construction engineering and management: A critical review and future trends. *Automation in Construction, 122*(February), 103517.

[53] Prebanić, K. R., & Vukomanović, M. (2021). Realizing the need for digital transformation of stakeholder management: A systematic review in the construction industry. *Sustainability (Switzerland), 13*(22), 12690.

[54] Qureshi, M. I., Khan, N., Qayyum, S., Malik, S., Sanil, H. S., & Ramayah, T. (2020). Classifications of sustainable manufacturing practices in ASEAN region: A systematic review and bibliometric analysis of the past decade of research. *Sustainability, 12*(21), 8950.

[55] Radziejowska, A., & Sobotka, B. (2021). Analysis of the social aspect of smart cities development: The example of smart sustainable buildings. *Energies, 14*(14), 4330.

[56] Saka, A. B., Chan, D. W. M., & Siu, F. M. F. (2020). Drivers of sustainable adoption of building information modelling (BIM) in the Nigerian construction small and medium-sized enterprises (SMEs). *Sustainability, 12*(9), 3710.

[57] Sawhney, A., Riley, M., & Irizarry, J. (2020). *Construction 4.0: An innovation platform for the built environment*. New York, NY: Routledge.

[58] Sherratt, F., Szabo, E., & Hallowell, M. R. (2025). Seeking a scientific and pragmatic approach to safety culture in the North American construction industry. *Safety Science, 181*(January), 106658.https://doi.org/10.1016/j.ssci.2024.106658

[59] Shi, Q., Zuo, J., Huang, R., Huang, J., & Pullen, S. (2013). Identifying the critical factors for green construction: An empirical study in China. *Habitat International, 40*(October), 1–8.

[60] Shojaei, A., Wang, J., & Fenner, A. (2020). Exploring the feasibility of blockchain technology as an infrastructure for improving built asset sustainability. *Built Environment Project and Asset Management, 10*(2), 184–199.

[61] Tahmasebinia, F., et al. (2020). Criteria development for sustainable construction manufacturing in Construction Industry 4.0: Theoretical and laboratory investigations. *Construction Innovation, 20*(3), 379–400.

[62] Thurairajah, N., & Goucher, D. (2013). Advantages and challenges of using BIM: A cost consultant's perspective. In T. S. Sulbaran (Ed.), *49th ASC Annual International Conference* (pp. 1–8). Associated Schools of Construction (ASC).

[63] Turner, C., Oyekan, J., & Stergioulas, L. K. (2021). Distributed manufacturing: A new digital framework for sustainable modular construction. *Sustainability, 13*(3), 1515.

[64] Urrea, C., & Kern, J. (2025). Recent advances and challenges in industrial robotics: A systematic review of technological trends and emerging applications. *Processes, 13*(3), 832.

[65] Wang, X., Wang, S., Song, X., & Han, Y. (2020). IoT-based intelligent construction system for prefabricated buildings: Study of operating mechanism and implementation in China. *Applied Sciences, 10*(18), 6311.

[66] Wangler, T., Roussel, N., Bos, F. P., Salet, T. A. M., & Flatt, R. J. (2019). Digital concrete: A review. *Cement and Concrete Research, 123*(September), 105780.

[67] Windapo, A. O. (2014). Examination of green building drivers in the South African construction industry: Economics versus ecology. *Sustainability, 6*(9), 6088–6106.

[68] Witkowski, K. (2017). Internet of things, big data, Industry 4.0 – Innovative solutions in logistics and supply chains management. *Procedia Engineering, 182*, 763–769.

[69] Won, D., Hwang, B.-G., & Binte Mohd Samion, N. K. (2022). Cloud computing adoption in the construction industry of Singapore: Drivers, challenges, and strategies. *Journal of Management in Engineering, 38*(2), 05021017.

[70] Yap, J. B. H., Lee, K. P. H., Skitmore, M., Lew, L. L., Lee, W. P., & Lester, D. (2023). Predictors to increase safety technology adoption in construction: An exploratory factor analysis for Malaysia. *Journal of Civil Engineering and Management, 29*(2), 157–170.

[71] Yap, J. B. H., Skitmore, M., Chong, J. R., & Hon, C. K. H. (2022a). Managerial measures to reduce rework and improve construction safety in a developing country: Malaysian case. *Journal of Civil Engineering and Management, 28*(8), 646–660.

[72] Yap, J. B. H., Skitmore, M., Lam, C. G. Y., Lee, W. P., & Lew, Y. L. (2022b). Advanced technologies for enhanced construction safety management: Investigating Malaysian perspectives. *International Journal of Construction Management*, 1–10. https://doi.org/10.1080/15623599.2022.2135951

[73] Yap, J. B. H., Teh, Y. H., Loo, S. C., Shavarebi, K., & Zamharira, B. S. (2024a). Green procurement in the construction industry: Unfolding new underlying barriers for a developing country context. *Journal of Civil Engineering and Management, 30*(7), 632–645.

[74] Yap, J. B. H., Teh, Y. H., Loo, S. C., & Sulaiman, Z. B. (2024b). Benefits of green procurement: Perspectives from the Malaysian construction industry. *International Journal of Construction Management, 24*(14), 1530–1539.

[75] Yasin, M. Y., Zain, M. A. B. M., & Hassan, M. H. Bin. (2022). Urbanization and growth of Greater Kuala Lumpur: Issues and recommendations for urban growth management. *Southeast Asia: A Multidisciplinary Journal, 22*(2), 4–19. https://doi.org/10.1108/seamj-02-2022-b1002

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