Modelling Bim–Circular Economy Integration for Construction Waste Minimisation in Malaysia: A Pls-Sem Approach

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DOI: https://doi.org/10.47772/IJRISS.2026.100600525

Received: 10 June 2026; Accepted: 15 June 2026; Published: 29 June 2026

ABSTRACT

Construction waste remains a persistent sustainability challenge in the construction industry, particularly as conventional project delivery often follows a linear model of material use, disposal, and limited recovery. This study examines how Building Information Modelling (BIM) and Circular Economy practices can be integrated to support construction waste minimisation in Malaysia. Specifically, the study investigates the relationships among BIM Use, Implementation Challenges, BIM–Circular Economy Integration, and Construction Waste Minimisation. A quantitative survey was conducted among 279 Malaysian construction industry practitioners, and the data were analysed using Partial Least Squares Structural Equation Modelling (PLS-SEM). The findings show that BIM–Circular Economy Integration has a significant positive effect on Construction Waste Minimisation, while BIM Use also directly contributes to waste reduction. However, BIM Use does not significantly influence BIM–Circular Economy Integration, suggesting that BIM adoption alone is insufficient unless it is intentionally aligned with circular economy objectives. Implementation Challenges strongly influence BIM–Circular Economy Integration but do not directly affect Construction Waste Minimisation. The mediation analysis further indicates that BIM–Circular Economy Integration significantly mediates the relationship between Implementation Challenges and Construction Waste Minimisation, but not the relationship between BIM Use and Construction Waste Minimisation. These findings highlight that effective waste minimisation requires more than digital adoption; it requires clear circular strategies, stronger organisational support, improved BIM standards, stakeholder collaboration, and practical mechanisms for material reuse, recycling, and recovery. This study contributes to sustainable construction literature by providing empirical evidence on BIM-enabled circular construction and its role in reducing construction waste in Malaysia.

Keywords: Building Information Modelling; Circular Economy; Construction Waste Minimisation; Sustainable Construction; PLS-SEM

INTRODUCTION

The construction industry plays an important role in economic development, infrastructure provision, and urban growth. However, it is also one of the most resource-intensive sectors, contributing significantly to material consumption, carbon emissions, and construction-related waste. The buildings and construction sector continues to consume large amounts of energy and materials while generating substantial environmental impacts (UNEP, 2025). This issue is especially critical in rapidly developing countries such as Malaysia, where urbanisation, infrastructure expansion, and housing demand continue to increase construction and demolition waste. In Malaysia, construction waste management remains a major sustainability concern. Conventional construction practices are still largely based on a linear "take–make–dispose" model, where materials are used and discarded with limited reuse or recovery. CIDB Malaysia has highlighted that a significant amount of materials delivered to construction sites may become waste, showing the need for more circular and resource-efficient practices (Nir et al., 2025). Poor material planning, inaccurate quantity estimation, design changes, rework, weak coordination, and limited waste segregation can increase material loss, project costs, and environmental impacts. Circular Economy (CE) has gained attention as an alternative approach to improve resource efficiency in the built environment. CE promotes reduction, reuse, recycling, recovery, and lifecycle-based decision-making. In construction, CE encourages waste prevention from the design stage, material reuse, recycling planning, and the treatment of building components as future resources rather than waste. Recent studies show that CE strategies can minimise construction and demolition waste when applied across project stages through stakeholder involvement, design for disassembly, material recovery planning, and digital documentation (Ferriz-Papi et al., 2024)(She et al., 2024). At the same time, Building Information Modelling (BIM) has emerged as a key digital enabler for sustainable construction. BIM supports project information management, design coordination, visualisation, quantity accuracy, clash detection, construction planning, and stakeholder communication. These functions are important because construction waste often results from fragmented information, poor coordination, late design changes, and inaccurate material estimation. (Aftab et al., 2024) emphasised that BIM-supported waste quantification is important for improving waste forecasting and construction waste management. The integration of BIM with CE practices offers a promising pathway for construction waste minimisation. BIM can support circular decision-making through material tracking, reusable material identification, recycling planning, and documentation for future recovery. Recent studies have also linked BIM with material passports, circularity assessment, and lifecycle data management, showing that digital tools can improve transparency and traceability of construction materials (Al-Qazzaz et al., 2025). Nevertheless, BIM–CE integration faces barriers such as limited BIM knowledge, high software costs, insufficient standards, poor collaboration, stakeholder resistance, weak management support, and limited CE awareness. Although BIM, CE, and construction waste management have been widely studied, many previous studies examine them separately. There is still limited empirical evidence explaining how BIM Use, Implementation Challenges, BIM–Circular Economy Integration, and Construction Waste Minimisation are structurally related. Therefore, this study proposes and tests a PLS-SEM model using survey data from 279 Malaysian construction practitioners. The study aims to examine the influence of BIM Use on BIM–Circular Economy Integration, assess the effect of Implementation Challenges, evaluate the impact of BIM–Circular Economy Integration on Construction Waste Minimisation, and determine its mediating role between BIM Use and Construction Waste Minimisation.

LITERATURE REVIEW

The construction industry is widely recognised as one of the most resource-intensive sectors in the global economy. While it contributes significantly to infrastructure, housing, and economic development, it is also associated with high material consumption, energy demand, carbon emissions, and construction and demolition waste. The latest Global Status Report for Buildings and Construction highlights that the sector continues to account for a substantial share of global energy use and emissions, with materials such as cement and steel contributing heavily to embodied carbon and waste generation (UNEP, 2025). This shows that sustainability in construction must go beyond operational energy efficiency and address how materials are designed, procured, used, recovered, and circulated throughout the project lifecycle. Construction waste is not merely a site-level issue. It often results from deeper project inefficiencies such as inaccurate quantity estimation, design errors, poor coordination, rework, over-ordering, weak material handling, and limited planning for reuse and recycling. In many projects, waste is still managed reactively after it has already been generated. This limits prevention because key decisions on design, material selection, and construction methods are usually made much earlier. Therefore, construction waste minimisation requires a shift from waste handling to waste prevention and from isolated site practices to lifecycle-based material management. Circular Economy (CE) offers an important response to this challenge. Unlike the linear “take, make, use and dispose” model, CE promotes a regenerative approach that aims to retain material value for as long as possible. In construction, this includes reducing unnecessary material use, designing for adaptability, planning for reuse and recycling, recovering components at the end of life, and improving information about material flows. CIDB Malaysia has also highlighted the relevance of circular economy thinking to the construction sector, particularly through reuse, recycling, low-carbon practices, and waste reduction (Nir et al., 2025). However, circular construction is not easy to implement. It requires early design decisions, reliable material information, supply-chain collaboration, supportive standards, and organisational willingness to change. Recent reviews show that although CE is increasingly discussed in research and policy, its implementation remains fragmented due to limited tools, data, incentives, and coordination mechanisms (Ferriz-Papi et al., 2024); (Rashidian et al., 2026)(Weerakoon et al., 2025).

Building Information Modelling (BIM) has emerged as a key digital enabler for construction waste minimisation. BIM allows project teams to create, manage, visualise, and share digital representations of project information. From a waste minimisation perspective, BIM is valuable because many causes of waste are information-related. BIM improves quantity take-off accuracy, reduces over-ordering, supports clash detection, minimises rework, improves planning and sequencing, and enhances communication among stakeholders. (Lins et al., 2024) noted that BIM applications in construction and demolition waste management are increasingly linked to waste minimisation, waste quantification, and lifecycle-based decision-making. Similarly, (Karanafti et al., 2024) argued that BIM can improve waste management by supporting reuse, recycling rates, and circularity. Nevertheless, BIM should not be viewed as a guaranteed solution to construction waste. BIM provides better information, but its impact depends on how that information is used. A project team may use BIM for design coordination but still fail to apply it for material recovery, circular procurement, or waste prevention. Therefore, BIM is not inherently circular; it becomes circular only when it is connected to reuse, recycling, recovery, resource efficiency, and sustainable material management. This argument is supported by studies that link BIM with circularity assessment, material passports, and digital material tracking. (Al-Qazzaz et al., 2025), for instance, proposed a BIM-based decision support system for circularity and sustainability assessment in early design, showing that BIM can support more transparent and circular material decisions.

CE practices in construction include waste reduction, material reuse, recycling, component recovery, design for disassembly, modular construction, selective demolition, waste segregation, recycled material use, and material passports. However, CE implementation remains uneven because it depends on stakeholder capability, procurement systems, market acceptance of recovered materials, and reliable material information. (Mandiˇcák et al., 2024) found that BIM and sustainable design can support CE principles by improving recycling rates, waste reduction, and CO_2 reduction. However, without accurate information on what materials are used, where they are located, and whether they can be reused or recycled, many recoverable materials are still treated as waste. (Mankata et al., 2025) emphasised that material passports can support construction waste management by documenting material information for reuse, recycling, refurbishment, and recovery. This shows that circularity requires strong information infrastructure, and BIM can provide a platform for storing and communicating circular material data.

The integration of BIM and CE represents a shift from using BIM only as a coordination tool to using it as a platform for circular value creation. BIM improves the availability and accuracy of project information, while CE provides the sustainability logic for keeping materials in use and reducing waste. Together, they can support material tracking, waste forecasting, design for disassembly, recycling planning, circularity assessment, and documentation for material recovery. (Banihashemi et al., 2024) argued that digital transformation can support CE in the built environment, although its role remains unevenly implemented. (Saka et al., 2024) further demonstrated that BIM combined with machine learning can predict the circularity of construction and demolition waste, showing the future direction of BIM-enabled circular construction. Despite its potential, BIM–CE integration faces several challenges, including lack of BIM training, high software and hardware costs, resistance to change, inadequate standards, insufficient data quality, poor collaboration, limited management support, and low CE awareness. These barriers are important because BIM adoption differs across organisations, and many firms still use BIM mainly for visualisation or coordination rather than circular material management. CE also requires collaboration among designers, contractors, suppliers, clients, waste managers, and regulators. (Alsofiani, 2024) identified barriers such as lack of education and training, resistance to change, unclear business value, perceived cost, lack of standards, and lack of mandates as major obstacles to BIM adoption. These barriers are especially relevant to BIM–CE integration because circular construction requires higher levels of coordination and data consistency.

Overall, the literature shows that BIM, CE, and construction waste minimisation are strongly connected, but several research gaps remain. Many studies discuss BIM and CE conceptually, but fewer empirically test the relationships among BIM Use, BIM–CE Integration, Implementation Challenges, and Construction Waste

Minimisation. There is also limited evidence from Malaysia, where construction digitalisation and circular economy adoption are still developing. Based on these gaps, this study proposes six hypotheses: H1, BIM Use positively influences BIM–Circular Economy Integration; H2, Implementation Challenges significantly influence BIM–Circular Economy Integration; H3, BIM–Circular Economy Integration positively influences Construction Waste Minimisation; H4, BIM Use positively influences Construction Waste Minimisation; H5, Implementation Challenges significantly influence Construction Waste Minimisation; and H6, BIM–Circular Economy Integration mediates the relationship between BIM Use and Construction Waste Minimisation. Thus, this study contributes by empirically modelling BIM Use, Implementation Challenges, BIM–Circular Economy Integration, and Construction Waste Minimisation among Malaysian construction practitioners.

METHODOLOGY

The study adopted a quantitative cross-sectional survey design to examine how Building Information Modelling (BIM) Use and Implementation Challenges influence BIM–Circular Economy Integration and Construction Waste Minimisation in the Malaysian construction industry. A quantitative approach was appropriate because the study aimed to test theoretically informed relationships among latent constructs rather than only describe industry perceptions. Since the data were collected at one point in time from construction practitioners with different levels of BIM, waste management, and circular construction exposure, a cross-sectional design was considered suitable. Partial Least Squares Structural Equation Modelling (PLS-SEM) was selected as the main analytical technique because it is appropriate for prediction-oriented studies involving multiple latent variables, reflective constructs, and mediation relationships. Following (Joseph F. Hair et al., 2022) and (Sarstedt et al., 2022), PLS-SEM was used to assess both the measurement quality of the constructs and the structural relationships among them.

The target population consisted of Malaysian construction industry practitioners involved directly or indirectly in project delivery, including architects, engineers, project engineers, site supervisors, BIM coordinators or modellers, quantity surveyors, contractors, consultants, developers, clients, and other related personnel. These respondents were considered suitable because BIM implementation, circular construction, and waste minimisation require input from multiple stakeholders. A purposive sampling approach was used to ensure that respondents had relevant construction-related knowledge or experience. The final dataset consisted of 279 valid responses, which was considered adequate for PLS-SEM and sufficient to test the proposed model.

Data were collected using a structured questionnaire developed based on the research objectives and conceptual framework. The instrument consisted of five sections. Section A collected demographic information, including position, years of experience, organisation type, BIM familiarity, BIM project involvement, knowledge of construction waste management, knowledge of circular construction, and involvement in circular construction projects. Section B measured BIM Use in supporting circular construction and waste reduction, including material quantity accuracy, waste reduction, coordination, clash detection, documentation, material tracking, and stakeholder communication. Section C measured Implementation Challenges, including lack of BIM training, high software cost, stakeholder resistance, limited standards, insufficient BIM data, poor collaboration, weak management support, and limited circular economy awareness. Section D measured BIM–Circular Economy Integration and Construction Waste Minimisation, including reusable material identification, recycling planning, resource efficiency, waste reduction, sustainable material management, material recovery, and project sustainability. Section E contained an open-ended question but was not included in the PLS-SEM model.

Items in Sections B, C, and D as shown in Table 1 were measured using a five-point Likert scale ranging from 1 = Strongly Disagree to 5 = Strongly Agree. Four reflective constructs were proposed: BIM Use, Implementation Challenges, BIM–Circular Economy Integration, and Construction Waste Minimisation. Before analysis, the data were screened for missing values, inconsistent responses, coding errors, and out-of-range values. SPSS was used for descriptive analysis, including frequencies, percentages, means, and standard deviations.

Common method bias was considered because the data were collected through a self-administered questionnaire. Procedural controls included confidentiality assurance and separating the items into different sections.

ISSN No. 2454-6186 | DOI: 10.47772/IJRISS | Volume X Issue VI June 2026

Statistically, the full collinearity approach may be applied, where common method bias is unlikely to be serious if the variance inflation factor values remain below the recommended threshold (Kock & Hadaya, 2018).

The PLS-SEM analysis followed a two-stage procedure. First, the measurement model was assessed using outer loadings, Cronbach's alpha, rho_A, composite reliability, Average Variance Extracted (AVE), and HTMT. Recommended thresholds included outer loadings above 0.708, reliability values above 0.70, AVE above 0.50, and HTMT values below 0.85 or 0.90. Second, the structural model was assessed using inner VIF, path coefficients, bootstrapping, t-values, p-values, confidence intervals, R^2, f^2, Q^2 or PLSpredict, and mediation analysis. Ethical considerations were addressed by ensuring voluntary participation, confidentiality, and the use of data solely for academic purposes.

Table 1: Constructs and measurement items

Items	Description
B	Current Use of BIM to Support Circular Construction & Waste Reduction
B1	BIM improves material quantity accuracy in my projects.
B2	BIM helps reduce material wastage on site.
B3	BIM enhances coordination and reduces rework.
B4	BIM enables early detection of design clashes.
B5	BIM supports documentation for reuse or recycling of materials.
B6	BIM contributes to circular construction practices in my organization.
B7	BIM improves material tracking throughout the construction process.
B8	BIM facilitates better communication and information sharing among project stakeholders.
C	Challenges in Implementing BIM for Circular Practices
C1	Lack of BIM training is a major challenge.
C2	High cost of BIM software limits implementation.
C3	Stakeholders are resistant to adopting BIM-based circular practices.
C4	Lack of BIM standards for circular construction hinders adoption.
C5	Insufficient BIM data limits sustainable decision-making.
C6	Poor collaboration affects BIM implementation for circular practice.
C7	Lack of management support limits the implementation of BIM for circular construction practices.
C8	Limited awareness of circular economy concepts among industry practitioners hinders BIM adoption.
D	Integration of BIM with Circular Economy Practices for Construction Waste Minimization
D1	BIM supports the identification of reusable construction materials.
D2	BIM facilitates planning for material recycling during construction projects.
D3	The integration of BIM and circular economy practices improves resource efficiency.
D4	BIM assists project teams in reducing construction waste generation.
D5	BIM enables better decision-making for sustainable material management.
D6	BIM supports design strategies that promote material recovery and reuse.
D7	The integration of BIM with circular economy practices contributes to construction waste minimization.
D8	Implementing BIM together with circular economy practices enhances overall project sustainability.

ISSN No. 2454-6186 | DOI: 10.47772/IJRISS | Volume X Issue VI June 2026

DATA ANALYSIS AND RESULTS

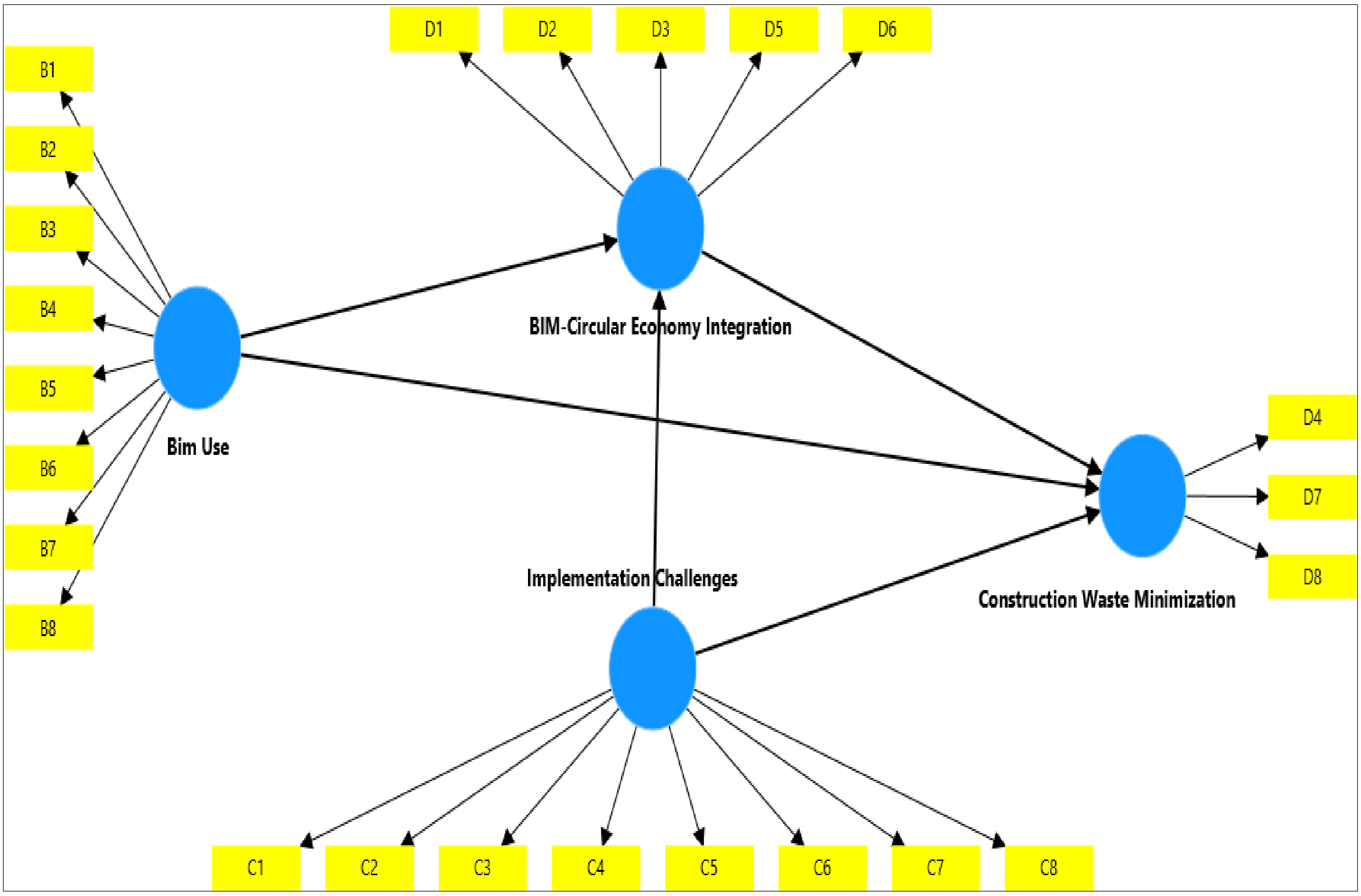

Figure 1: Assessment model

Proposed assessment model as shown in Figure 1 developed to examine the relationship between BIM Use, Implementation Challenges, BIM–Circular Economy Integration, and Construction Waste Minimisation. The model consists of four latent constructs measured by their respective indicators. BIM Use is measured using eight items, B1 to B8, which represent the application of BIM in areas such as material quantity accuracy, waste reduction, coordination, clash detection, documentation, material tracking, and stakeholder communication. Implementation Challenges is measured using items C1 to C8, reflecting barriers such as lack of training, high software cost, stakeholder resistance, lack of standards, insufficient BIM data, poor collaboration, lack of management support, and limited awareness of circular economy practices. BIM–Circular Economy Integration is represented by five indicators, D1, D2, D3, D5, and D6. These items capture the role of BIM in supporting reusable material identification, recycling planning, resource efficiency, sustainable material management, and material recovery. Construction Waste Minimisation is measured using three indicators, D4, D7, and D8, which focus on reducing construction waste generation, supporting waste minimisation, and enhancing overall project sustainability. The structural paths in the model show the hypothesised relationships among the constructs. BIM Use is expected to influence BIM–Circular Economy Integration and Construction Waste Minimisation. This suggests that BIM functions may support both circular construction practices and direct waste reduction. Implementation Challenges are also linked to BIM–Circular Economy Integration and Construction Waste Minimisation, indicating that barriers may affect the successful implementation of digital and circular strategies. In addition, BIM–Circular Economy Integration is positioned as a key predictor of Construction Waste Minimisation. This reflects the assumption that BIM contributes more effectively to waste reduction when it is integrated with circular economy practices. Overall, the model provides a clear framework for testing both direct and indirect relationships. It supports the study's main argument that construction waste minimisation can be better understood by examining not only BIM adoption, but also circular economy integration and the challenges that influence implementation.

ISSN No. 2454-6186 | DOI: 10.47772/IJRISS | Volume X Issue VI June 2026

Respondents' Demographic Profile

Table 2: Demographic Profile of Respondents

Respondent Profile		Frequency	Percent (%)
A1. Position in the construction industry	Architect	31	11%
	Engineer	165	59%
	Supervisor	47	17%
	BIM Modeler	23	8%
	Quantity Surveyor	13	5%
A2. Years of experience in the construction industry	Less than 1 year	20	7%
	1–3 years	32	11%
	4–7 years	92	33%
	8–10 years	62	22%
	More than 10 years	73	26%
A3. Organization type	Developer/Client	35	13%
	Architect Firm	80	29%
	Consultant	83	30%
	Contractor	81	29%
A6. Level of knowledge in Construction Waste Management	Very Low	23	8%
	Low	18	6%
	Moderate	16	6%
	High	125	45%
	Very High	97	35%
A7. Level of knowledge in Circular Construction practices	Very Low	18	6%
	Low	12	4%
	Moderate	49	18%
	High	97	35%
	Very High	103	37%
A8. Have you been involved in any construction project that implements circular construction practices?	Yes	239	86%
	No	40	14%
	Total	279	

Demographic profile of the 279 respondents in Table 2 who participated in this study. The majority of respondents were engineers, representing 59% of the sample, followed by supervisors at 17%, architects at 11%, BIM modelers at 8%, and quantity surveyors at 5%. This shows that the sample was mainly represented by technical construction professionals who are directly involved in design coordination, project planning, site implementation, and construction decision-making. In terms of experience, most respondents had 4 to 7 years of experience in the construction industry, accounting for 33% of the sample. This was followed by respondents with more than 10 years of experience at 26%, those with 8 to 10 years at 22%, 1 to 3 years at 11%, and less than 1 year at 7%. This indicates that most respondents had moderate to extensive industry experience, strengthening the credibility of their views on BIM use, circular construction practices, and construction waste management. The respondents were also well distributed across different organisation types. Consultants formed the largest group at 30%, followed by contractors and architect firms, each at 29%, while developer/client organisations represented 13%. This balanced representation suggests that the study captured perspectives from various stages of construction project delivery, including design, consultancy, contracting, and client-related roles. Regarding knowledge of construction waste management, most respondents reported high or very high knowledge, representing 45% and 35%, respectively. Similarly, knowledge of circular construction practices was also strong, with 37% reporting very high knowledge and 35% reporting high knowledge. Furthermore, 86% of respondents had been involved in projects implementing circular construction practices, while only 14%

had no such experience. Overall, the respondent profile indicates that the sample was suitable for this study. The respondents were experienced construction professionals from various organisation types, with strong knowledge and practical exposure to construction waste management and circular construction practices. Therefore, their responses provide a credible basis for analysing BIM–Circular Economy integration and construction waste minimisation in Malaysia.

Descriptive Statistics

Table 3: Descriptive Statistics of the Main Constructs

Main constructs	N	Mean	Std. Deviation
Bim_Use	279	3.806	1.136
Implementation_Challenges	279	3.830	0.966
BIM_Circular_Economy_Integration	279	3.898	1.040
Construction_Waste_Minimisation	279	3.961	0.992
Valid N (listwise)	279		

Descriptive statistics (Table 3) for the main constructs examined in this study. Overall, the mean scores ranged from 3.806 to 3.961, indicating that respondents generally agreed with the statements related to BIM use, implementation challenges, BIM–Circular Economy integration, and construction waste minimisation. Construction Waste Minimisation recorded the highest mean score (M = 3.961, SD = 0.992), suggesting that respondents perceived BIM–Circular Economy practices as important for reducing construction waste. This was followed by BIM–Circular Economy Integration (M = 3.898, SD = 1.040), Implementation Challenges (M = 3.830, SD = 0.966), and BIM Use (M = 3.806, SD = 1.136). The standard deviation values indicate a moderate variation in respondents' perceptions, with BIM Use showing the highest variability. Overall, the results suggest that Malaysian construction practitioners hold generally positive views toward BIM–Circular Economy integration and its potential contribution to construction waste minimisation.

Measurement Model Assessment

Table 4: Indicator Reliability Based on Outer Loadings

	Outer loadings
B1 <- Bim Use	0.903
B2 <- Bim Use	0.801
B3 <- Bim Use	0.835
B4 <- Bim Use	0.884
B5 <- Bim Use	0.879
B6 <- Bim Use	0.860
B7 <- Bim Use	0.883
B8 <- Bim Use	0.909
C1 <- Implementation Challenges	0.856
C2 <- Implementation Challenges	0.848
C3 <- Implementation Challenges	0.815
C4 <- Implementation Challenges	0.823
C5 <- Implementation Challenges	0.915
C6 <- Implementation Challenges	0.809
C7 <- Implementation Challenges	0.810
C8 <- Implementation Challenges	0.712
D1 <- BIM-Circular Economy Integration	0.867
D2 <- BIM-Circular Economy Integration	0.787
D3 <- BIM-Circular Economy Integration	0.855

D4 <- Construction Waste Minimization	0.907
D5 <- BIM-Circular Economy Integration	0.864
D6 <- BIM-Circular Economy Integration	0.842
D7 <- Construction Waste Minimization	0.846
D8 <- Construction Waste Minimization	0.889

The results in Table 4 of the outer loadings for all measurement items in the model show that all indicators exceeded the recommended threshold of 0.708, with loading values ranging from 0.714 to 0.914. For BIM Use, the outer loadings ranged from 0.801 to 0.909, indicating that all eight items strongly represented the construct. Similarly, Implementation Challenges recorded acceptable loadings between 0.714 and 0.914, confirming that the items were suitable for measuring perceived barriers to BIM–Circular Economy implementation. For BIM–Circular Economy Integration, the loadings ranged from 0.787 to 0.867, while Construction Waste Minimisation showed strong loadings between 0.846 and 0.907. These results indicate that the indicators were reliable and contributed meaningfully to their respective constructs. Therefore, no items were removed from the measurement model. Overall, the outer loading results support the indicator reliability of the model and confirm that the measurement items were appropriate for further reliability, validity, and structural model assessment.

Table 5: Construct Reliability and Convergent Validity

Construct	Cronbach's alpha	Composite reliability (rho_a)	Composite reliability (rho_c)	Average variance extracted (AVE)
BIM-Circular Economy Integration	0.899	0.903	0.925	0.712
Bim Use	0.954	0.955	0.961	0.757
Construction Waste Minimization	0.855	0.855	0.912	0.776
Implementation Challenges	0.932	0.936	0.944	0.681

Table 5 shows the reliability and convergent validity results for the measurement model. The results indicate that all constructs achieved satisfactory internal consistency, with Cronbach's alpha values ranging from 0.855 to 0.954. Similarly, the composite reliability values, including rho_a and rho_c, exceeded the recommended threshold of 0.70 for all constructs, confirming that the items consistently measured their respective constructs. Although BIM Use recorded a relatively high composite reliability value ($rho\_c = 0.961$), it remained acceptable and suggests strong consistency among the BIM-related indicators. Convergent validity was also established, as all Average Variance Extracted (AVE) values exceeded the recommended minimum value of 0.50. The AVE values ranged from 0.681 for Implementation Challenges to 0.776 for Construction Waste Minimisation, indicating that each construct explained more than half of the variance in its indicators. Overall, the findings confirm that the measurement model demonstrated adequate reliability and convergent validity, making it suitable for further discriminant validity and structural model assessment.

Table 6: Discriminant Validity Assessment Using HTMT

	Heterotrait-monotrait ratio (HTMT)
Bim Use <-> BIM-Circular Economy Integration	0.909
Construction Waste Minimization <-> BIM-Circular Economy Integration	1.009
Construction Waste Minimization <-> Bim Use	0.944
Implementation Challenges <-> BIM-Circular Economy Integration	1.016
Implementation Challenges <-> Bim Use	0.943
Implementation Challenges <-> Construction Waste Minimization	0.984

The results in Table 6 show that all HTMT values exceeded the recommended threshold of 0.90, ranging from 0.909 to 1.016. This indicates that discriminant validity was not fully established among the constructs. In particular, the HTMT values for Construction Waste Minimisation and BIM–Circular Economy Integration (HTMT = 1.009), Implementation Challenges and BIM–Circular Economy Integration (HTMT = 1.016), and

Implementation Challenges and Construction Waste Minimisation (HTMT = 0.984) suggest a high degree of conceptual and empirical overlap. These findings imply that respondents may have perceived BIM use, circular economy integration, implementation challenges, and waste minimisation as closely connected rather than clearly separate constructs. While this overlap is theoretically understandable because the constructs are related within the BIM–Circular Economy context, the high HTMT values indicate that the measurement model requires careful interpretation. Therefore, the structural model results should be discussed cautiously, and future studies may refine the questionnaire items to improve distinction between the constructs.

Structural Model Assessment

Table 7: Structural Model Path Coefficients and Hypothesis Testing

H	Path	Original sample (O)	Sample mean (M)	Standard deviation (STDEV)	T statistics (|O/STDEV|)	P values
H1	Bim Use -> BIM-Circular Economy Integration	0.068	0.065	0.085	0.804	0.422
H2	Implementation Challenges -> BIM-Circular Economy Integration	0.872	0.875	0.078	11.225	0.000
H3	BIM-Circular Economy Integration -> Construction Waste Minimization	0.507	0.509	0.129	3.932	0.000
H4	Bim Use -> Construction Waste Minimization	0.300	0.296	0.093	3.217	0.001
H5	Implementation Challenges -> Construction Waste Minimization	0.142	0.143	0.149	0.952	0.341

Table 7 presents the path coefficient results for the structural model. The findings show that BIM Use did not have a significant effect on BIM–Circular Economy Integration, $\beta = 0.068$, $t = 0.804$, $p = 0.422$. Therefore, H1 was not supported. This suggests that BIM use alone may not automatically lead to stronger BIM–Circular Economy integration unless it is supported by other organisational or implementation factors. Implementation Challenges had a strong and significant effect on BIM–Circular Economy Integration, $\beta = 0.872$, $t = 11.225$, $p < 0.001$. Thus, H2 was supported. This result indicates that perceived implementation challenges were strongly associated with BIM–Circular Economy integration. In this context, respondents who were more aware of BIM–Circular Economy practices may also have been more aware of the barriers affecting their implementation. BIM–Circular Economy Integration had a significant positive effect on Construction Waste Minimisation, $\beta = 0.507$, $t = 3.932$, $p < 0.001$, supporting H3. This finding suggests that integrating BIM with circular economy practices can contribute meaningfully to reducing construction waste through better material reuse, recycling planning, resource efficiency, and sustainable material management. BIM Use also had a significant positive effect on Construction Waste Minimisation, $\beta = 0.300$, $t = 3.217$, $p = 0.001$. Therefore, H4 was supported. This indicates that BIM functions such as material quantity accuracy, coordination, clash detection, and material tracking can directly support waste reduction in construction projects. However, Implementation Challenges did not have a significant direct effect on Construction Waste Minimisation, $\beta = 0.142$, $t = 0.952$, $p = 0.341$. Thus, H5 was not supported. This suggests that although implementation challenges are strongly linked to BIM–Circular Economy integration, they do not directly explain construction waste minimisation in this model. Overall, the results indicate that construction waste minimisation is mainly influenced by BIM–Circular Economy Integration and

BIM Use, while Implementation Challenges appear to operate more strongly through the integration process rather than through a direct pathway.

Table 8: Coefficient of Determination for Endogenous Constructs

Endogenous Constructs	R-square	R-square adjusted
BIM-Circular Economy Integration	0.872	0.871
Construction Waste Minimization	0.832	0.831

The R^2 results for the endogenous constructs in the structural model (Table 8). The results show that BIM–Circular Economy Integration recorded an R^2 value of 0.872 and an adjusted R^2 value of 0.871. This indicates that 87.2% of the variance in BIM–Circular Economy Integration was explained by its predictor constructs, suggesting a substantial level of explanatory power. Construction Waste Minimisation recorded an R^2 value of 0.832 and an adjusted R^2 value of 0.831. This means that 83.2% of the variance in Construction Waste Minimisation was explained by BIM Use, Implementation Challenges, and BIM–Circular Economy Integration. Overall, the results indicate that the proposed model has strong explanatory power in explaining both BIM–Circular Economy Integration and Construction Waste Minimisation.

Table 9: Effect Size Assessment Using f^2 Values

	f-square
BIM-Circular Economy Integration -> Construction Waste Minimization	0.196
Bim Use -> BIM-Circular Economy Integration	0.008
Bim Use -> Construction Waste Minimization	0.113
Implementation Challenges -> BIM-Circular Economy Integration	1.238
Implementation Challenges -> Construction Waste Minimization	0.011

Table 9 results of the effect size, f^2, for each structural path in the model. The results show that Implementation Challenges had a large effect on BIM–Circular Economy Integration, $f^2 = 1.238$, indicating that this construct made a substantial contribution to explaining BIM–Circular Economy Integration. This suggests that perceived challenges play an important role in shaping how BIM and circular economy practices are integrated in construction projects. BIM–Circular Economy Integration had a small-to-medium effect on Construction Waste Minimisation, $f^2 = 0.196$, while BIM Use had a small effect on Construction Waste Minimisation, $f^2 = 0.113$. These findings indicate that both BIM–Circular Economy Integration and BIM Use contributed to explaining construction waste minimisation, although the effect of BIM–Circular Economy Integration was stronger. In contrast, BIM Use had a very small effect on BIM–Circular Economy Integration, $f^2 = 0.008$, and Implementation Challenges had a very small effect on Construction Waste Minimisation, $f^2 = 0.011$. These results suggest that the direct contribution of these paths was limited. Overall, the f^2 results indicate that Implementation Challenges strongly influenced BIM–Circular Economy Integration, while Construction Waste Minimisation was mainly supported by BIM–Circular Economy Integration and BIM Use.

Table 10: Predictive Relevance and Predictive Performance Using PLSpredict

	Q^2predict	PLS-SEM_RMSE	PLS-SEM_MAE	LM_RMSE	LM_MAE
D4	0.593	0.653	0.531	0.666	0.400
D7	0.650	0.681	0.497	0.640	0.315
D8	0.592	0.776	0.682	0.750	0.450

The Q^2predict values in Table 10 for D4, D7, and D8 were all greater than zero, ranging from 0.592 to 0.650. This indicates that the model demonstrated predictive relevance for all indicators of Construction Waste Minimisation. However, the comparison between the PLS-SEM and linear model (LM) prediction errors shows mixed results. For D4, the PLS-SEM model produced a lower RMSE value than the LM benchmark, suggesting better predictive performance for this indicator based on RMSE. In contrast, for D7 and D8, the LM produced lower RMSE values than the PLS-SEM model. For MAE, the LM values were lower than the PLS-SEM values for all three indicators. Overall, the results indicate that the model has predictive relevance because all Q²predict values were positive. Nevertheless, the model shows limited out-of-sample predictive power when compared with the linear model benchmark, as the LM generally produced lower prediction errors. Therefore, the proposed model is useful for explaining Construction Waste Minimisation, but its predictive performance should be interpreted cautiously.

Table 11: Collinearity Assessment Using Variance Inflation Factor Values

	VIF
BIM-Circular Economy Integration -> Construction Waste Minimization	7.806
Bim Use -> BIM-Circular Economy Integration	4.780
Bim Use -> Construction Waste Minimization	4.819
Implementation Challenges -> BIM-Circular Economy Integration	4.780
Implementation Challenges -> Construction Waste Minimization	10.700

Table 11 presents the variance inflation factor (VIF) values used to assess collinearity among the predictor constructs in the structural model. The results show that several VIF values exceeded the commonly recommended threshold of 5.00. Specifically, the path from BIM–Circular Economy Integration to Construction Waste Minimisation recorded a VIF value of 7.806, while the path from Implementation Challenges to Construction Waste Minimisation recorded the highest VIF value of 10.700. These values indicate the presence of multicollinearity among the predictors of Construction Waste Minimisation. The VIF values for BIM Use to BIM–Circular Economy Integration, BIM Use to Construction Waste Minimisation, and Implementation Challenges to BIM–Circular Economy Integration were below 5.00, ranging from 4.780 to 4.819. Although these values are still relatively high, they remain within an acceptable range based on the more lenient threshold. Overall, the VIF results suggest that collinearity may be a concern in the structural model, particularly for the predictors of Construction Waste Minimisation. This finding should be interpreted together with the high HTMT values reported earlier, as both results indicate that the constructs may be conceptually and empirically overlapping. Therefore, the structural model findings should be discussed cautiously, and future studies may refine or separate the measurement items more clearly to reduce construct overlap.

Hypothesis Testing

Table 12: Structural Model Hypothesis Testing Summary

Hypothesis	Relationship	Direction	Result	Practical meaning
H1	BIM Use → BIM–Circular Economy Integration	Positive	Not supported	BIM use alone is not enough to drive circular integration.
H2	Implementation Challenges → BIM–Circular Economy Integration	Positive	Supported	Challenges strongly shape awareness and implementation of BIM–CE practices.
H3	BIM–Circular Economy Integration → Construction Waste Minimisation	Positive	Supported	BIM–CE integration helps reduce construction waste.
H4	BIM Use → Construction Waste Minimisation	Positive	Supported	BIM directly supports waste reduction through coordination, accuracy, and tracking.
H5	Implementation Challenges → Construction Waste Minimisation	Positive	Not supported	Challenges do not directly reduce or explain waste minimisation outcomes.

Table 12 summarises the hypothesis testing results for the structural model. Overall, three hypotheses were supported, while two were not supported. H1 was not supported, although the relationship between BIM Use and BIM–Circular Economy Integration was positive. This suggests that BIM use alone may not be sufficient to promote circular integration unless it is supported by circular economy objectives, organisational commitment, and proper implementation strategies. H2 was supported, indicating that Implementation Challenges had a positive and significant relationship with BIM–Circular Economy Integration. This implies that challenges such

ISSN No. 2454-6186 | DOI: 10.47772/IJRISS | Volume X Issue VI June 2026

as training, cost, standards, collaboration, and management support strongly shape how BIM–CE practices are understood and implemented. H3 was also supported, showing that BIM–Circular Economy Integration contributes positively to Construction Waste Minimisation. This confirms that integrating BIM with circular practices can support waste reduction through material reuse, recycling planning, and better resource management. H4 was supported, suggesting that BIM Use directly contributes to Construction Waste Minimisation through improved coordination, quantity accuracy, clash detection, material tracking, and communication. However, H5 was not supported, meaning that Implementation Challenges did not directly explain Construction Waste Minimisation. Overall, the results suggest that waste minimisation is mainly influenced by BIM Use and BIM–Circular Economy Integration, while implementation challenges affect waste outcomes more indirectly through the integration process.

Mediation Analysis

Table 13: Mediation Analysis Based on Specific Indirect Effects

	Original sample (O)	Sample mean (M)	Standard deviation (STDEV)	T statistics (|O/STDEV|)	P values
Bim Use -> BIM-Circular Economy Integration -> Construction Waste Minimization	0.036	0.034	0.045	0.795	0.427
Implementation Challenges -> BIM-Circular Economy Integration -> Construction Waste Minimization	0.441	0.444	0.121	3.645	0.000

Table 13 presents the mediation analysis based on the specific indirect effects. The indirect effect of BIM Use on Construction Waste Minimisation through BIM–Circular Economy Integration was positive but not significant, $\beta = 0.036$, $t = 0.795$, $p = 0.427$. Therefore, BIM–Circular Economy Integration did not significantly mediate the relationship between BIM Use and Construction Waste Minimisation. This suggests that although BIM Use had a small positive indirect effect, its contribution to waste minimisation through BIM–Circular Economy Integration was not statistically meaningful. In contrast, the indirect effect of Implementation Challenges on Construction Waste Minimisation through BIM–Circular Economy Integration was positive and significant, $\beta = 0.441$, $t = 3.645$, $p < 0.001$. This indicates that BIM–Circular Economy Integration significantly mediated the relationship between Implementation Challenges and Construction Waste Minimisation. Practically, this means that implementation challenges influence construction waste minimisation mainly through their connection with BIM–Circular Economy Integration. In other words, issues such as training, cost, standards, collaboration, and management support shape how BIM and circular economy practices are integrated, and this integration subsequently affects waste minimisation outcomes. Overall, the mediation results show that BIM–Circular Economy Integration plays a significant mediating role for Implementation Challenges but not for BIM Use. Therefore, the indirect pathway from Implementation Challenges to Construction Waste Minimisation through BIM–Circular Economy Integration is supported, while the indirect pathway from BIM Use to Construction Waste Minimisation is not supported.

DISCUSSION

The study examined how BIM Use, Implementation Challenges, and BIM–Circular Economy Integration explain Construction Waste Minimisation in the Malaysian construction industry. Overall, the findings provide a useful but nuanced picture. The model showed strong explanatory power, with BIM–Circular Economy Integration and Construction Waste Minimisation achieving high R^2 values. This suggests that the proposed model is relevant for explaining how digital construction and circular economy practices can support waste reduction. However, the results also show that the relationship is not as simple as assuming that BIM adoption alone will automatically produce circular and sustainable outcomes.

ISSN No. 2454-6186 | DOI: 10.47772/IJRISS | Volume X Issue VI June 2026

The non-significant relationship between BIM Use and BIM–Circular Economy Integration is an important finding. Although BIM Use showed a positive direction, the effect was weak and statistically insignificant. This suggests that BIM, when used mainly for design coordination, quantity take-off, clash detection, or communication, may not directly translate into circular economy integration. In practice, many organisations may use BIM as a technical project delivery tool rather than as a platform for circular material management. This finding is consistent with recent discussions that BIM can support circular construction, but only when it is deliberately connected to material passports, reuse planning, recycling strategies, lifecycle data, and end-of-life decision-making (Al-Qazzaz et al., 2025)(Mankata et al., 2025). Therefore, BIM should not be treated as inherently circular. Its circular value depends on how project teams use BIM information to support material recovery, resource efficiency, and waste prevention.

The strongest relationship in the model was between Implementation Challenges and BIM–Circular Economy Integration. This finding may appear unusual at first because challenges are often expected to reduce implementation. However, in this study, the positive and significant relationship can be interpreted as an awareness effect. Respondents who recognised BIM–Circular Economy integration more strongly may also have been more aware of the barriers surrounding its implementation. These barriers include lack of BIM training, high software costs, lack of standards, poor collaboration, insufficient data, limited management support, and weak awareness of circular economy concepts. This finding supports recent literature showing that the transition towards circular construction is not limited by technology alone, but also by organisational readiness, data availability, stakeholder collaboration, and policy support (Banihashemi et al., 2024)(Ferriz-Papi et al., 2024). In other words, practitioners may understand the potential of BIM–Circular Economy integration, but they are also conscious of the practical difficulties that must be addressed before this integration can be widely implemented.

The significant effect of BIM–Circular Economy Integration on Construction Waste Minimisation confirms the central argument of this study. When BIM is linked to circular economy practices, it can support better identification of reusable materials, recycling planning, resource efficiency, sustainable material management, and material recovery. This finding is aligned with recent studies that emphasise the role of BIM, material passports, and digital material information in improving circularity in construction (Mankata et al., 2025)(Saka et al., 2024). The result suggests that waste minimisation should begin earlier in the project lifecycle, especially during planning and design, rather than being treated only as a site-level waste management issue. BIM–Circular Economy integration allows project teams to move from reactive waste disposal towards proactive waste prevention.

The direct effect of BIM Use on Construction Waste Minimisation was also significant. This shows that BIM can still contribute to waste reduction even without fully developed circular economy integration. BIM functions such as accurate material quantity estimation, clash detection, design coordination, and improved communication can reduce rework, over-ordering, and material wastage. This supports the view that BIM improves construction efficiency and can reduce avoidable waste during project delivery. However, the effect size was smaller than the contribution of BIM–Circular Economy Integration. This means that BIM is useful for waste reduction, but its impact becomes more meaningful when it is connected to circular principles such as reuse, recycling, recovery, and lifecycle-based material planning.

In contrast, Implementation Challenges did not have a significant direct effect on Construction Waste Minimisation. This suggests that barriers do not directly explain waste minimisation outcomes in the model. Instead, their influence appears to operate indirectly through BIM–Circular Economy Integration. The mediation result supports this interpretation, as BIM–Circular Economy Integration significantly mediated the relationship between Implementation Challenges and Construction Waste Minimisation. Practically, this means that challenges such as cost, training, standards, and collaboration affect waste minimisation mainly because they shape how effectively BIM and circular economy practices are integrated. Therefore, reducing construction waste requires more than identifying barriers; it requires transforming these barriers into targeted improvement strategies, such as BIM training, standardised material information, circular procurement guidelines, and stronger management commitment.

Nevertheless, the findings must be interpreted critically. The HTMT results showed high values among several constructs, and the VIF results also indicated collinearity concerns, particularly among predictors of Construction Waste Minimisation. This suggests that respondents may have perceived BIM use, BIM–Circular Economy integration, implementation challenges, and waste minimisation as closely connected rather than clearly separate concepts. While this overlap is theoretically understandable, it raises a methodological concern. Future studies should refine the measurement items so that each construct captures a more distinct dimension. For example, BIM Use items should focus only on digital BIM functions, BIM–Circular Economy Integration items should focus on circular material processes, and Construction Waste Minimisation items should focus on measurable waste reduction outcomes.

The PLSpredict results also require careful interpretation. The positive Q^2predict values indicate that the model has predictive relevance for Construction Waste Minimisation. However, the comparison with the linear model benchmark showed mixed predictive performance. This means that the model explains the data well, but its out-of-sample predictive strength is more limited. For a Q1-style interpretation, this is an important point because a strong R^2 value alone does not guarantee strong predictive performance. The model is therefore useful for explaining the relationships among the constructs, but further validation with new samples, project-level waste data, or longitudinal research would strengthen its predictive robustness.

Overall, the study contributes to the sustainable construction literature by showing that BIM and circular economy practices should not be treated as separate agendas. BIM provides the digital information environment, while circular economy provides the sustainability logic for material reuse, recycling, recovery, and waste prevention. The findings suggest that construction waste minimisation in Malaysia can be improved when BIM is intentionally used to support circular material decisions. However, the study also shows that implementation challenges, construct overlap, and limited predictive performance must be taken seriously. The practical implication is clear: the industry should move beyond basic BIM adoption and focus on BIM-enabled circular construction strategies supported by training, standards, collaboration, reliable data, and organisational commitment.

CONCLUSION

The role of BIM–Circular Economy integration in supporting construction waste minimisation in the Malaysian construction industry. The findings show that BIM–Circular Economy Integration and BIM Use significantly contribute to Construction Waste Minimisation, suggesting that digital construction tools can support waste reduction when they are applied meaningfully across project planning, coordination, material tracking, reuse, recycling, and sustainable material management. However, BIM Use did not significantly influence BIM–Circular Economy Integration, indicating that BIM adoption alone is insufficient unless it is deliberately aligned with circular economy objectives. The study also found that Implementation Challenges strongly influenced BIM–Circular Economy Integration, while their direct effect on Construction Waste Minimisation was not significant. This suggests that challenges such as lack of training, high software cost, limited standards, poor collaboration, and weak management support affect waste minimisation mainly through their impact on BIM–Circular Economy implementation. Therefore, improving construction waste minimisation requires more than adopting BIM technology; it requires stronger organisational readiness, clearer BIM standards for circular construction, better stakeholder collaboration, and stronger industry awareness of circular economy practices. Overall, this study contributes to sustainable construction research by empirically modelling the relationship between BIM Use, Implementation Challenges, BIM–Circular Economy Integration, and Construction Waste Minimisation. The findings provide useful evidence for construction practitioners, policymakers, and BIM managers in Malaysia to move beyond basic BIM adoption towards a more integrated digital-circular approach. Future research should refine the measurement items, address construct overlap, and include project-level waste data to strengthen the predictive validity of the model.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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