The Role of BIM and Artificial Intelligence in Reducing the Environmental Impacts of Construction Projects: A Sustainable Construction Management Approach

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Abstract

This study aimed to examine the role of Building Information Modeling (BIM) and artificial intelligence in reducing the environmental impacts of construction projects with an emphasis on sustainable construction management. This applied quantitative study was conducted using a descriptive-correlational design. The statistical population consisted of construction professionals, engineers, project managers, BIM specialists, construction management experts, architects, and environmental consultants working in construction projects in Tehran. A total of 284 participants were selected through purposive sampling based on professional experience and familiarity with construction technologies or sustainable construction practices. Data were collected using structured questionnaires measuring BIM application in construction management, artificial intelligence application in construction projects, environmental impact reduction, and sustainable construction management. The questionnaires were scored on a five-point Likert scale, and their content validity was confirmed by experts. Reliability was assessed using Cronbach's alpha coefficients. Data were analyzed using descriptive statistics, Pearson correlation, and multiple regression analysis at a significance level of 0.05. The inferential results showed that BIM application was positively and significantly correlated with environmental impact reduction ($r = 0.68$, $p < 0.01$) and sustainable construction management ($r = 0.62$, $p < 0.01$). Artificial intelligence application also had significant positive correlations with environmental impact reduction ($r = 0.67$, $p < 0.01$) and sustainable construction management ($r = 0.64$, $p < 0.01$). Environmental impact reduction was strongly associated with sustainable construction management ($r = 0.73$, $p < 0.01$). Regression analysis showed that BIM alone explained 46% of the variance in environmental impact reduction, while the combined model of BIM and artificial intelligence explained 51% of the variance. Both BIM ($\beta = 0.44$, $p < 0.001$) and artificial intelligence ($\beta = 0.42$, $p < 0.001$) significantly predicted environmental impact reduction. In addition, BIM, artificial intelligence, and environmental impact reduction significantly predicted sustainable construction management and explained 62% of its variance. The findings indicate that BIM and artificial intelligence are effective digital enablers for reducing the environmental impacts of construction projects and strengthening sustainable construction management. Their integrated application can improve design coordination, resource optimization, waste reduction, carbon control, and data-driven decision-making in construction projects.

Keywords: *Building Information Modeling; Artificial Intelligence; Environmental Impact Reduction; Sustainable Construction Management; Construction Projects; Digital Construction*

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1. Introduction

The construction industry is one of the most resource-intensive sectors of the global economy and plays a central role in shaping patterns of energy consumption, material use, waste generation, land transformation, and carbon emissions. As urbanization, infrastructure expansion, and building demand continue to increase, the environmental consequences of construction activities have become a critical concern for governments, project owners, contractors, designers, and researchers. Construction projects consume large quantities of raw materials, generate substantial construction and demolition waste, and often involve complex supply chains that intensify greenhouse gas emissions across the project lifecycle. In response to these challenges, sustainable construction management has emerged as an essential approach for aligning project planning, design, execution, operation, and maintenance with environmental protection, resource efficiency, and long-term lifecycle performance. However, traditional construction management methods often remain fragmented, document-based, and reactive, making it difficult to predict environmental impacts, optimize resource consumption, reduce rework, and coordinate sustainability decisions across multiple stakeholders. The transition toward digital, intelligent, and data-driven construction therefore represents an important pathway for improving environmental performance and strengthening sustainable management practices in the built environment [1-3].

Building Information Modeling (BIM) has become one of the most influential digital technologies in contemporary construction management because it provides an integrated platform for generating, managing, coordinating, and analyzing project information throughout the lifecycle of a building or infrastructure asset. BIM enables project stakeholders to create multidimensional digital representations of physical and functional characteristics, thereby improving design coordination, cost estimation, scheduling, constructability analysis, clash detection, lifecycle planning, and facility management. From the perspective of sustainability, BIM provides a structured environment in which environmental criteria can be considered earlier and more systematically in decision-making. Through BIM-based simulation and information integration, project teams can evaluate material quantities, compare design alternatives, estimate energy performance, identify sources of waste, reduce errors and rework, and improve coordination among architects, engineers, contractors, and owners. These capabilities are particularly important because environmental impacts in construction are often determined by early design and planning decisions, while the consequences appear later during execution, operation, and maintenance. Studies on BIM use in infrastructure and construction projects have shown that BIM can improve management efficiency, strengthen information reliability, support sustainable planning, and reduce the environmental burden associated with inefficient design and execution processes [4-7].

Despite the growing adoption of BIM, the complexity of environmental management in construction projects requires more than digital modeling alone. Construction projects generate large and heterogeneous datasets from design models, schedules, cost systems, sensors, procurement processes, machinery, site monitoring tools, environmental reports, and facility operation systems. Artificial intelligence (AI) offers a powerful set of methods for extracting patterns, predicting outcomes, optimizing decisions, and supporting automated or semi-automated management processes based on these data. AI applications in construction include machine learning, deep learning, computer vision, natural language processing, generative AI, predictive analytics, optimization algorithms, intelligent decision-support systems, and autonomous monitoring tools. These technologies can support different phases of the project lifecycle, including design optimization, risk prediction, cost forecasting, safety monitoring, quality control, energy analysis, waste prediction, and carbon emission reduction. In sustainable construction management, AI can assist managers in identifying environmentally inefficient practices, predicting the consequences of design and execution decisions, optimizing resource allocation, and improving the responsiveness of project teams to emerging sustainability risks [8-11].

The integration of BIM and AI is especially significant because these two technologies have complementary strengths. BIM provides structured, semantically rich, and lifecycle-oriented project information, while AI provides the analytical capacity to process complex data, identify hidden relationships, generate predictions, and recommend optimized actions. In isolation, BIM may improve visualization, coordination, and information management, but its environmental benefits depend on how effectively the information embedded in models is analyzed and used in decision-making. Similarly, AI requires reliable, structured, and contextualized data to produce useful predictions and recommendations. When AI is integrated with BIM, project teams can move from descriptive digital modeling toward predictive and prescriptive construction management. This integration can support environmental impact reduction by enabling automated detection of design conflicts, prediction of material waste, optimization of energy performance, estimation of carbon emissions, intelligent scheduling of construction activities, simulation of alternative construction methods, and lifecycle-based evaluation of sustainability outcomes. Therefore, BIM and AI together can create a more intelligent construction management ecosystem in which environmental decisions are based on integrated information, predictive analytics, and continuous feedback [1, 12-14].

In recent years, the concept of digital twins has further expanded the potential of BIM and AI for sustainable construction. A digital twin refers to a dynamic digital representation of a physical asset, system, or process that can be continuously updated through real-time or near-real-time data. In the construction and built environment sectors, digital twins can connect BIM models with sensors, Internet of Things systems, artificial intelligence, geographic information systems, and operational data to monitor performance, simulate scenarios, and support lifecycle decision-making. Digital twin technologies are particularly relevant to sustainability because they can provide continuous information on energy use, environmental conditions, structural performance, occupancy patterns, resource consumption, and maintenance needs. When combined with AI, digital twins can improve predictive maintenance, optimize building operation, reduce energy consumption, detect inefficiencies, and support zero-energy or low-carbon building strategies. Recent research has emphasized that AI-powered digital twins can contribute to smart, green, and zero-energy buildings by connecting design-stage information with operational intelligence and environmental performance goals [15-18].

The environmental value of BIM, AI, and digital twin integration is not limited to individual buildings. These technologies are increasingly being discussed in relation to sustainable cities, resilient infrastructure, industrial urban areas, campuses, transportation networks, and large-scale infrastructure systems. The built environment is a complex system in which buildings, roads, utilities, public spaces, industrial facilities, and digital networks interact with environmental, social, and economic processes. Therefore, sustainable construction management requires attention to both project-level and system-level impacts. Data-driven approaches that combine BIM, GIS, remote sensing, AI, and digital twins can support net-zero carbon monitoring, urban metabolism assessment, infrastructure sustainability analysis, and resilience planning. For example, digital technologies can help monitor carbon emissions across urban systems, evaluate the environmental performance of infrastructure networks, analyze material flows, and improve the sustainability of civil engineering assets over their lifecycle. Such capabilities are essential for moving from isolated sustainability measures toward integrated environmental governance in construction and urban development [19-22].

The transition toward intelligent and sustainable construction is also linked to broader transformations associated with the Fourth and Fifth Industrial Revolutions. The Fourth Industrial Revolution has introduced cyber-physical systems, automation, cloud computing, big data analytics, IoT, AI, and advanced visualization into engineering and construction practice. These technologies are reshaping how construction projects are designed, managed, monitored, and delivered. At the same time, the concept of Industry 5.0 emphasizes human-centered, resilient, and sustainable technological development, suggesting that digital transformation should not merely improve productivity but also contribute to environmental responsibility, social value, and long-term resilience. In this context, sustainable construction management requires a balance between technological innovation and managerial capacity. Digital tools can generate information and recommendations, but project managers, engineers, and decision-makers must interpret these outputs, align them with sustainability objectives, and embed them into organizational processes. Therefore, the adoption of BIM and AI should be understood not only as a technical change but also as a managerial transformation that affects coordination, communication, accountability, and environmental decision-making in construction projects [2, 3, 9, 23].

AI and BIM also have important implications for design visualization, immersive interaction, and stakeholder communication. Sustainable construction decisions often require the participation of different stakeholders, including designers, engineers, contractors, clients, regulators, facility managers, and end users. Miscommunication among these actors can result in design errors, inefficient construction methods, material waste, delayed decisions, and poor environmental outcomes. BIM improves communication by providing shared visual and informational models, while AI and immersive technologies can enhance visualization, augmented realism, interactivity, and simulation. These capabilities allow stakeholders to better understand design alternatives, environmental consequences, construction sequences, and operational scenarios before physical work begins. AI-supported architectural visualization can improve interactive decision-making, while immersive technologies combined with BIM can support sustainable smart city planning, design review, training, and performance evaluation. In this way, digital technologies can reduce environmental impacts not only through technical optimization but also through improved collaboration, shared understanding, and more informed decision-making among project participants [24-26].

The application of AI and BIM is also relevant to special construction contexts, including reconstruction, renovation, road projects, industrial facilities, and infrastructure modernization. Sustainable management in these contexts is complex because projects often involve existing assets, uncertain conditions, limited resources, time pressure, safety concerns, and strong environmental constraints. BIM can provide a reliable information base for documenting existing conditions, planning interventions, and coordinating renovation or reconstruction activities. AI can strengthen this process by supporting damage assessment, condition monitoring, optimization of reconstruction alternatives, predictive planning, and intelligent resource management. The integration of BIM with artificial intelligence of things and smart monitoring technologies can be particularly useful in reconstruction and renovation because it allows project teams to combine digital models with real-time information from buildings and construction sites. In road and infrastructure projects, BIM uses and complementary technologies can also support more sustainable planning, resource management, and lifecycle maintenance, especially when projects extend across large geographic areas and involve significant environmental disturbance [4, 6, 18, 27].

Although the literature increasingly supports the potential of BIM, AI, digital twins, IoT, and related technologies for sustainability, important challenges remain in their practical implementation. These challenges include lack of interoperability among software platforms, limited data quality, insufficient digital skills, high implementation costs, resistance to organizational change, fragmented project delivery systems, cybersecurity risks, unclear standards, and limited integration between design-stage models and construction-site or operation-stage data. In many construction organizations, BIM is still used mainly for visualization or clash detection rather than environmental performance management, while AI remains at an early stage of adoption and is often limited to isolated pilot applications. Moreover, sustainability outcomes are difficult to achieve when digital technologies are not embedded into management routines, contractual relationships, procurement systems, and performance evaluation frameworks. The effectiveness of BIM and AI in reducing environmental impacts therefore depends on the extent to which these technologies are integrated into construction management processes and connected to measurable sustainability objectives [8-10, 12].

Carbon reduction is one of the most important environmental priorities in contemporary construction management. The building and infrastructure sectors contribute to carbon emissions through embodied carbon in materials, energy use during construction, transportation, machinery operation, waste management, and operational energy consumption across the asset lifecycle. AI-based carbon emission analysis can help construction managers identify high-emission activities, compare alternative materials and methods, optimize project schedules, and develop targeted reduction strategies. BIM can support this process by providing structured data on quantities, materials, spatial relationships, design alternatives, and lifecycle information. When AI-based carbon analysis is connected with BIM models, project teams can evaluate environmental implications more accurately and earlier in the project lifecycle. This is particularly important because reducing carbon emissions requires not only operational efficiency but also better design choices, procurement decisions, construction methods, and maintenance strategies. Therefore, AI-supported BIM can help transform environmental management from a retrospective reporting activity into a proactive and predictive process [13, 15, 19].

Sustainable construction management also requires a lifecycle perspective. Environmental impacts are not confined to the construction phase but occur across design, procurement, execution, operation, maintenance, renovation, and end-of-life stages. AI-powered civil engineering throughout the entire lifecycle emphasizes the need to integrate data and intelligence across these phases rather than treating them separately. BIM provides the lifecycle information structure, digital twins provide dynamic performance representation, and AI provides predictive and optimization capabilities. Together, these technologies can support whole-life sustainability assessment, performance monitoring, adaptive management, and continuous improvement. In intelligent construction, multidimensional modeling and interactive simulation can enable managers to test scenarios, anticipate risks, and optimize environmental outcomes before decisions are implemented in the physical environment. This lifecycle integration is essential for sustainable construction because decisions made at one stage often affect resource consumption, emissions, maintenance needs, and waste generation at later stages [11, 14, 16, 17].

Despite the growing body of international research on BIM, AI, and sustainability in construction, there remains a need for empirical studies that examine how professionals perceive and evaluate the role of these technologies in reducing environmental impacts within specific construction markets. Many existing studies are systematic reviews, conceptual frameworks, bibliometric analyses, or technology-focused discussions, while fewer studies provide field-based evidence from construction professionals regarding the relationship among BIM application, AI application, environmental impact reduction, and sustainable construction management. This gap is important because the success of digital sustainability tools depends heavily on professional awareness, organizational readiness, project delivery practices, and local construction conditions. In rapidly developing urban contexts such as Tehran, construction projects face pressures related to resource efficiency, environmental degradation, waste production, energy demand, and the need for modern project management systems. Examining the views of construction professionals in such contexts can provide useful evidence for understanding whether BIM and AI are perceived as practical tools for environmental improvement and how they may contribute to sustainable construction management.

The aim of this study was to examine the role of BIM and artificial intelligence in reducing the environmental impacts of construction projects with a sustainable construction management approach.

2. Methodology

This study was conducted using an applied, quantitative, descriptive-correlational design. The purpose of the study was to examine the role of Building Information Modeling (BIM) and artificial intelligence in reducing the environmental impacts of construction projects with an emphasis on sustainable construction management. The statistical population consisted of professionals, experts, and managers active in the construction industry in Tehran, including project managers, civil engineers, architects, construction management specialists, BIM coordinators, environmental consultants, and technical experts working in construction companies, consulting engineering firms, and project management organizations. The participants were selected from active building and infrastructure projects in Tehran during the study period. The final sample included 284 participants who met the inclusion criteria and completed the questionnaires accurately. The inclusion criteria were having at least a bachelor's degree in architecture, civil engineering, construction management, environmental engineering, urban planning, or related fields; having at least three years of professional experience in construction projects; and having sufficient familiarity with BIM, digital construction technologies, or sustainable construction practices. Participants who submitted incomplete questionnaires or had no direct professional experience in construction projects were excluded from the analysis. Sampling was carried out through purposive sampling, because the study required respondents with specialized knowledge of construction technologies and environmental management in building projects. Before data collection, the objectives of the study were explained to the participants, and informed consent was obtained. Participation was voluntary, and respondents were assured that their information would remain confidential and would be used only for research purposes.

Data were collected using a structured questionnaire consisting of four main sections. The first section included demographic and professional information, such as age, gender, level of education, academic field, years of professional experience, organizational position, type of construction activity, and previous experience with BIM-based or AI-supported construction processes. This section was designed to describe the characteristics of the participants and to ensure that the respondents had sufficient professional background to answer the specialized items of the study.

The second section was the BIM Application in Construction Management Questionnaire, which was designed to assess the extent to which BIM was used in construction project planning, design coordination, resource management, clash detection, cost estimation, scheduling, lifecycle assessment, and environmental performance monitoring. The questionnaire included 18 items scored on a five-point Likert scale ranging from 1, meaning "very low," to 5, meaning "very high." Higher scores indicated greater application of BIM in construction management processes. The items covered dimensions such as digital modeling, integration of project information, coordination among project stakeholders, simulation of construction processes, optimization of material use, and support for sustainable decision-making. The content validity of this questionnaire was reviewed and confirmed by a panel of construction management, BIM, and environmental engineering experts. Its reliability was also examined in a pilot study, and the Cronbach's alpha coefficient confirmed acceptable internal consistency.

The third section was the Artificial Intelligence Application in Construction Projects Questionnaire, which measured the use of AI-based tools and techniques in predicting project risks, optimizing resource allocation, improving energy efficiency, supporting decision-making, reducing waste, monitoring site performance, and analyzing environmental data. This questionnaire consisted of 16 items scored on a five-point Likert scale from 1, meaning "very low," to 5, meaning "very high." Higher scores represented a higher level of AI application in construction project management. The items focused on the use of machine learning, predictive analytics, intelligent monitoring systems, automated decision-support systems, image-based site monitoring, and data-driven optimization methods. The validity of the questionnaire was assessed through expert review, and necessary modifications were made based on their comments. Reliability was evaluated using Cronbach's alpha, and the obtained coefficient indicated that the questionnaire had acceptable reliability for use in the present study.

The fourth section was the Environmental Impact Reduction and Sustainable Construction Management Questionnaire. This instrument was used to measure the perceived contribution of digital technologies to reducing environmental impacts in construction projects. It included 22 items scored on a five-point Likert scale ranging from 1, meaning "strongly disagree," to 5, meaning "strongly agree." The questionnaire assessed dimensions such as reduction of construction waste, efficient use of materials, reduction of energy consumption, reduction of carbon emissions, improvement of water and resource management, prevention of design errors and rework, lifecycle-based decision-making, and alignment with sustainable construction management principles. Higher scores indicated a stronger perceived reduction in environmental impacts and a higher level of sustainable management performance. The content validity of this tool was confirmed by specialists in sustainable construction, environmental management, and construction project management. The reliability of the instrument was assessed using Cronbach's alpha, and the results showed satisfactory internal consistency.

After the questionnaires were collected, the data were reviewed, coded, and entered into statistical software for analysis. Incomplete or invalid questionnaires were removed before the final analysis. Descriptive statistics, including frequency, percentage, mean, and standard deviation, were used to describe the demographic and professional characteristics of the participants and the main research variables. The normality of the data distribution was examined using skewness, kurtosis, and the Kolmogorov–Smirnov test. The internal consistency of the questionnaires was assessed using Cronbach's alpha coefficient. Pearson correlation analysis was used to examine the relationships among BIM application, artificial intelligence application, environmental impact reduction, and sustainable construction management. Multiple regression analysis was then performed to determine the predictive role of BIM and artificial intelligence in reducing the environmental impacts of construction projects. In addition, the assumptions of regression analysis, including linearity, independence of errors, multicollinearity, and homoscedasticity, were examined before interpreting the final model. The significance level for all statistical analyses was considered at 0.05.

3. Findings and Results

The demographic findings showed that 284 professionals and experts active in construction projects in Tehran participated in the study. Of the participants, 188 individuals were male (66.2%) and 96 individuals were female (33.8%). The age of the respondents ranged from 24 to 58 years, with a mean age of 36.84 years and a standard deviation of 7.91, indicating that the sample consisted mainly of early- to mid-career and experienced professionals. In terms of educational level, 118 participants held a bachelor's degree (41.5%), 134 participants held a master's degree (47.2%), and 32 participants held a doctoral degree (11.3%). Regarding professional experience, 54 participants had between 3 and 5 years of experience (19.0%), 89 participants had between 6 and 10 years of experience (31.3%), 75 participants had between 11 and 15 years of experience (26.4%), and 66 participants had more than 15 years of experience in construction-related fields (23.2%). With respect to occupational position, the sample included civil engineers, architects, project managers, BIM coordinators, construction management specialists, environmental consultants, and technical experts. More specifically, 72 participants were civil engineers (25.4%), 46 were architects (16.2%), 63 were project managers (22.2%), 38 were BIM coordinators or BIM specialists (13.4%), 41 were construction management experts (14.4%), and 24 were environmental consultants or technical specialists (8.5%). In terms of organizational affiliation, 129 participants worked in construction companies (45.4%), 91 in consulting engineering firms (32.0%), 42 in project management organizations (14.8%), and 22 in environmental or technical service organizations related to construction projects (7.7%). Moreover, 199 participants (70.1%) reported previous experience with BIM-based processes, 153 participants (53.9%) reported experience with artificial intelligence or data-driven tools in construction management, and 217 participants (76.4%) reported familiarity with sustainable construction management principles. Overall, the demographic and professional characteristics of the respondents indicated that the sample had sufficient expertise and practical experience to evaluate the role of BIM and artificial intelligence in reducing the environmental impacts of construction projects.

Table 1. Descriptive Statistics and Reliability of the Main Research Variables

Variable	Number of Items	Mean	Standard Deviation	Minimum	Maximum	Skewness	Kurtosis	Cronbach's Alpha
BIM application in construction management	18	3.71	0.62	2.11	4.94	-0.28	-0.19	0.89
Artificial intelligence application in construction projects	16	3.54	0.67	1.88	4.88	-0.21	-0.34	0.91
Environmental impact reduction	22	3.82	0.58	2.23	4.96	-0.33	-0.12	0.93
Sustainable construction management	15	3.76	0.61	2.07	4.93	-0.26	-0.27	0.90

As shown in Table 1, the mean scores of the main research variables were higher than the theoretical midpoint of the five-point scale, indicating that the respondents generally evaluated the application of BIM, the use of artificial intelligence, the reduction of environmental impacts, and sustainable construction management at a relatively favorable level. The highest mean score belonged to environmental impact reduction (M = 3.82, SD = 0.58), suggesting that participants perceived digital construction technologies as meaningfully contributing to the reduction of waste, energy consumption, design errors, rework, and inefficient resource use in construction projects. Sustainable construction management also showed a relatively high mean score (M = 3.76, SD = 0.61), indicating that the participants believed sustainability-oriented planning, resource optimization, lifecycle-based decision-making, and environmental control were increasingly integrated into construction project management processes. The mean score for BIM application was 3.71 (SD = 0.62), reflecting a relatively strong level of BIM adoption in design coordination, project planning, modeling, clash detection, and information integration. The mean score for artificial intelligence application was 3.54 (SD = 0.67), which, although favorable, was slightly lower than the other variables, suggesting that AI-based tools were used in construction projects but had not yet reached the same level of institutionalization as BIM. The skewness and kurtosis values of all variables were within the acceptable range, supporting the assumption of approximate normality. In addition, Cronbach's alpha coefficients ranged from 0.89 to 0.93, confirming the strong internal consistency and reliability of all instruments used in the study.

Table 2. Pearson Correlation Matrix Among BIM, Artificial Intelligence, Environmental Impact Reduction, and Sustainable Construction Management

Variable	1	2	3	4
1. BIM application in construction management	1			
2. Artificial intelligence application in construction projects	0.57**	1		
3. Environmental impact reduction	0.68**	0.67**	1	
4. Sustainable construction management	0.62**	0.64**	0.73**	1

The correlation results presented in Table 2 showed significant and positive relationships among all main research variables. BIM application in construction management was positively and significantly correlated with environmental impact reduction ($r = 0.68$, $p < 0.01$), indicating that greater use of BIM was associated with stronger perceived reductions in the environmental impacts of construction projects. This relationship suggests that BIM may contribute to environmental improvement through more accurate design coordination, reduction of errors and rework, better material estimation, improved scheduling, and enhanced lifecycle-based project control. Artificial intelligence application was also positively and significantly correlated with environmental impact reduction ($r = 0.67$, p

< 0.01), showing that higher use of AI-based tools, such as predictive analytics, intelligent monitoring systems, optimization algorithms, and automated decision-support systems, was associated with better environmental performance in construction projects. BIM and artificial intelligence were also positively related to sustainable construction management, with correlation coefficients of 0.62 and 0.64, respectively. These findings indicate that both technologies are connected not only to direct environmental outcomes but also to broader managerial practices that support sustainability. The strongest correlation was observed between environmental impact reduction and sustainable construction management ($r = 0.73$, $p < 0.01$), suggesting that projects managed according to sustainable construction principles are more likely to achieve reductions in waste, energy consumption, carbon emissions, and inefficient use of resources. Overall, the correlation matrix confirmed the conceptual assumption of the study that BIM and artificial intelligence are closely linked to environmental performance and sustainability-oriented construction management.

Table 3. Multiple Regression Model Summary for Predicting Environmental Impact Reduction Based on BIM and Artificial Intelligence

Model	Predictor Variables	R	R²	Adjusted R²	Standard Error of Estimate	F	df	p
Model 1	BIM application	0.68	0.46	0.46	0.43	241.18	1, 282	<0.001
Model 2	BIM application and artificial intelligence application	0.72	0.51	0.51	0.41	147.89	2, 281	<0.001

The regression model summary in Table 3 indicated that BIM application alone significantly predicted environmental impact reduction in construction projects. In Model 1, BIM application explained 46% of the variance in environmental impact reduction ($R^2 = 0.46$, adjusted $R^2 = 0.46$), and the model was statistically significant, $F(1, 282) = 241.18$, $p < 0.001$. This finding shows that the use of BIM in construction management is a strong predictor of reduced environmental impacts, especially because BIM can improve design accuracy, prevent conflicts between disciplines, reduce construction errors, improve material planning, and support more efficient project execution. In Model 2, artificial intelligence application was added to the regression model alongside BIM application. The combined model explained 51% of the variance in environmental impact reduction ($R^2 = 0.51$, adjusted $R^2 = 0.51$), and the model remained statistically significant, $F(2, 281) = 147.89$, $p < 0.001$. The increase in explained variance from 46% to 51% demonstrated that artificial intelligence added meaningful predictive value beyond BIM alone. This means that although BIM plays a central role in environmental performance improvement, the integration of AI-based methods strengthens this role by enabling predictive analysis, risk detection, automated optimization, intelligent monitoring, and data-driven decision-making. Therefore, the combined use of BIM and artificial intelligence provides a stronger explanatory model for reducing the environmental effects of construction projects than the use of BIM alone.

Table 4. Regression Coefficients for Predicting Environmental Impact Reduction

Predictor Variable	B	Standard Error	Beta	t	p	Tolerance	VIF
Constant	0.86	0.16	—	5.37	<0.001	—	—
BIM application in construction management	0.41	0.04	0.44	9.36	<0.001	0.67	1.49
Artificial intelligence application in construction projects	0.36	0.04	0.42	8.82	<0.001	0.67	1.49

The regression coefficients presented in Table 4 showed that both BIM application and artificial intelligence application were significant positive predictors of environmental impact reduction. BIM application had a standardized beta coefficient of 0.44 ($B = 0.41$, $SE = 0.04$, $t = 9.36$, $p < 0.001$), indicating that BIM had the strongest predictive contribution in the final regression model. This result means that for every one-unit increase in BIM application, the environmental impact reduction score increased by 0.41 units, when the effect of artificial intelligence was controlled. This finding highlights the importance of BIM as a central digital platform for sustainable construction management, because BIM allows project teams to coordinate design information, simulate construction processes, estimate materials more accurately, identify clashes before execution, reduce unnecessary rework, and support lifecycle-based environmental decision-making. Artificial intelligence application was also a significant predictor of environmental impact reduction, with a standardized beta coefficient of 0.42 (B = 0.36, SE = 0.04, t = 8.82, $p < 0.001$). This result means that for every one-unit increase in AI application, the environmental impact reduction score increased by 0.36 units, when BIM application was controlled. The finding confirms that AI can contribute to sustainable construction by supporting predictive modeling, optimization of resource allocation, energy performance analysis, waste prediction, smart monitoring, and real-time decision support. The tolerance values and VIF statistics indicated that multicollinearity was not a concern in the regression model, because tolerance values were above 0.10 and VIF values were below the conservative threshold of 5. Therefore, the regression coefficients were stable and suitable for interpretation. Overall, the results showed that BIM and artificial intelligence each had independent and significant contributions to reducing the environmental impacts of construction projects.

Table 5. Regression Analysis for Predicting Sustainable Construction Management Based on BIM, Artificial Intelligence, and Environmental Impact Reduction

Predictor Variable	B	Standard Error	Beta	t	p
Constant	0.64	0.15	—	4.27	<0.001
BIM application in construction management	0.22	0.04	0.23	5.48	<0.001
Artificial intelligence application in construction projects	0.25	0.04	0.27	6.16	<0.001
Environmental impact reduction	0.42	0.05	0.40	8.71	<0.001

The results of Table 5 demonstrated that BIM application, artificial intelligence application, and environmental impact reduction significantly predicted sustainable construction management. The total regression model was statistically significant and explained a substantial proportion of the variance in sustainable construction management (R = 0.79, $R^2 = 0.62$, adjusted $R^2 = 0.61$, $F(3, 280) = 151.84$, $p < 0.001$). Among the predictor variables, environmental impact reduction had the strongest standardized effect on sustainable construction management ($\beta = 0.40$, $p < 0.001$), indicating that projects with greater reductions in waste, energy use, carbon emissions, material inefficiency, and rework were more likely to demonstrate stronger sustainable management performance. Artificial intelligence application was also a significant predictor of sustainable construction management ($\beta = 0.27$, $p < 0.001$), showing that AI-based analysis, forecasting, optimization, and intelligent control systems can improve managerial decisions related to sustainability. BIM application also had a significant positive effect ($\beta = 0.23$, $p < 0.001$), confirming that digital modeling, integrated project information, design coordination, and lifecycle-based planning support the implementation of sustainable construction management practices. These findings suggest that sustainable construction management is not achieved through isolated environmental measures alone, but through the combined use of digital modeling, intelligent data analysis, and systematic environmental performance control. Therefore, BIM and artificial intelligence appear to function as complementary technological foundations for sustainable construction management, while environmental impact reduction acts as a key operational outcome through which these technologies support broader sustainability performance.

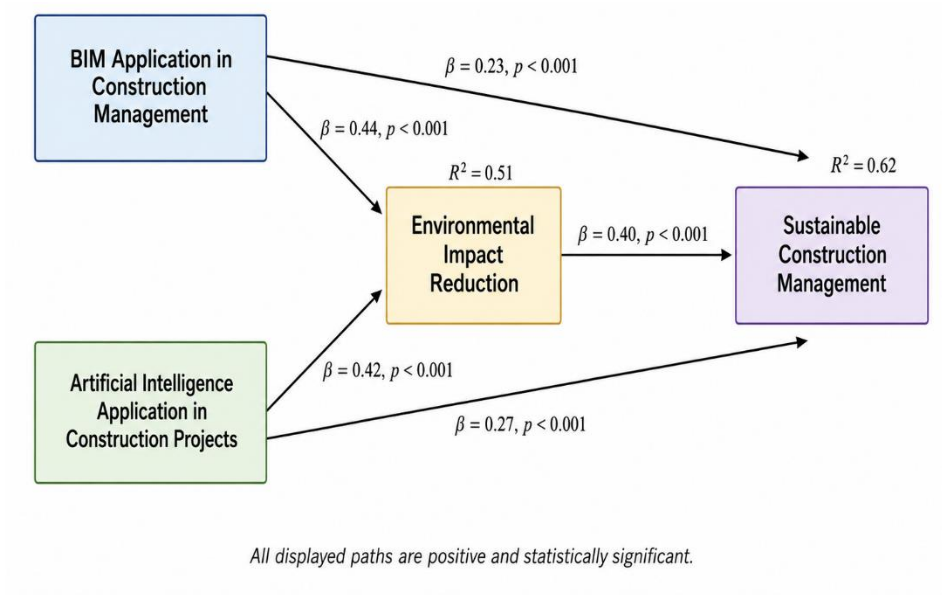

Figure 1. Predictive Role of BIM and Artificial Intelligence in Reducing Environmental Impacts and Strengthening Sustainable Construction Management

Figure 1 illustrates the overall pattern of relationships identified in the findings of the study. The model shows that BIM and artificial intelligence both have direct positive effects on environmental impact reduction and sustainable construction management. BIM contributes to environmental improvement by enabling accurate design modeling, coordination among project stakeholders, reduction of construction errors, optimization of materials, simulation of project processes, and improved lifecycle management. Artificial intelligence strengthens this process by adding predictive, analytical, and optimization capabilities to construction management. Through AI-based tools, project teams can forecast risks, identify inefficient resource use, monitor site conditions, predict waste generation, evaluate energy performance, and support real-time decision-making. The model also shows that environmental impact reduction is strongly related to sustainable construction management, indicating that reducing waste, energy consumption, carbon emissions, water use, and unnecessary rework is a central pathway toward sustainability in construction projects. Overall, the figure summarizes the main empirical result of the study: the integration of BIM and artificial intelligence provides a stronger basis for sustainable construction management than the separate or limited use of digital tools, because these technologies jointly improve information accuracy, prediction capacity, environmental control, and managerial decision-making in construction projects.

4. Discussion and Conclusion

The present study examined the role of BIM and artificial intelligence in reducing the environmental impacts of construction projects with a sustainable construction management approach. The findings showed that the respondents evaluated BIM application, artificial intelligence application, environmental impact reduction, and sustainable construction management at relatively favorable levels. The descriptive results indicated that environmental impact reduction had the highest mean score among the main variables, followed by sustainable construction management, BIM application, and artificial intelligence application. This pattern suggests that construction professionals in Tehran increasingly recognize the environmental value of digital technologies, while the practical use of AI-based tools appears to be less institutionalized than BIM. This finding is consistent with the broader literature indicating that BIM has already become a more established digital platform in construction management, whereas AI, machine learning, generative AI, and AI-supported decision systems are still developing across many construction organizations and project delivery environments [8, 9, 12]. The relatively strong reliability coefficients obtained for the research instruments also confirmed that the measured constructs were internally coherent and suitable for evaluating the relationship among digital construction technologies, environmental performance, and sustainable management.

The correlation findings showed significant and positive relationships among BIM application, artificial intelligence application, environmental impact reduction, and sustainable construction management. BIM application was significantly associated with environmental impact reduction, indicating that greater use of BIM in construction management was linked to stronger perceived reductions in waste, energy consumption, design errors, rework, and inefficient material use. This result aligns with prior studies emphasizing that BIM contributes to sustainability by improving information integration, clash detection, material estimation, lifecycle planning, and coordination among stakeholders [4-6]. BIM allows project teams to evaluate design alternatives and construction sequences before execution, which can reduce environmentally costly errors during the physical construction phase. In this regard, BIM does not merely function as a visualization tool; rather, it serves as a managerial and analytical platform that supports more accurate planning and environmentally informed decision-making. The findings are also consistent with research on digitalization and sustainability trends in linear and infrastructure projects, which suggests that digital models can improve environmental control when they are integrated into project management processes rather than used only for technical representation [6, 7].

The positive correlation between artificial intelligence application and environmental impact reduction also supports the argument that AI-based tools can strengthen sustainable construction practices. The results indicated that higher use of AI in construction projects was associated with improved environmental performance. This finding is compatible with studies showing that AI and machine learning can support prediction, optimization, classification, automation, and intelligent monitoring across the project lifecycle [8, 11]. In sustainable construction, AI can contribute to waste prediction, energy performance analysis, construction risk forecasting, smart monitoring, carbon emission analysis, and resource optimization. The result is also aligned with studies that identify AI, IoT, big data, and cloud-based construction technologies as central tools for improving efficiency and sustainability in the architecture, engineering, and construction sector [9, 10, 26]. AI can process complex and heterogeneous project data more rapidly than traditional management systems and can detect patterns that may not be visible through conventional project control methods. Therefore, the observed relationship between AI and environmental impact reduction reflects the growing managerial relevance of intelligent analytics in construction sustainability.

The regression results further showed that BIM application was a strong predictor of environmental impact reduction. BIM alone explained 46% of the variance in environmental impact reduction, which indicates that BIM plays a substantial role in improving environmental outcomes in construction projects. This finding can be explained by the capacity of BIM to reduce uncertainty and fragmentation in project information. Many environmental inefficiencies in construction are caused by design inconsistencies, inaccurate quantity estimation, poor coordination, delayed decision-making, and rework. BIM directly addresses these problems by creating a shared digital information environment that improves the accuracy and consistency of project decisions. Previous studies on BIM and infrastructure management similarly show that BIM-based approaches can enhance construction management performance by improving coordination, technical planning, and information reliability [4, 5]. From a sustainable management perspective, the predictive role of BIM suggests that environmental impact reduction should be treated as an integral outcome of digital project coordination. When BIM is applied effectively, environmental benefits emerge not only through energy simulation or green design analysis, but also through everyday managerial improvements such as fewer clashes, less rework, more accurate material orders, and better scheduling.

When artificial intelligence was added to the regression model, the explained variance increased to 51%, showing that AI added meaningful predictive value beyond BIM alone. This result supports the idea that BIM and AI are complementary technologies. BIM provides structured project data, while AI provides the computational capacity to analyze this data, generate predictions, optimize alternatives, and support intelligent decision-making. This interpretation is consistent with recent research on AI-powered civil engineering, which emphasizes that AI can enhance performance across the entire lifecycle of civil engineering projects [11]. It is also aligned with studies on AI-based carbon emission analysis and reduction strategies, which indicate that AI can support targeted environmental decision-making in construction projects by identifying high-emission processes and proposing reduction strategies [13]. Therefore, the findings suggest that the environmental value of BIM becomes stronger when it is integrated with AI-based analytics. In practical terms, BIM may show what the project is, how it is organized, and where resources are used, while AI may predict what will happen, where inefficiencies will occur, and which alternative will produce better environmental outcomes.

The regression coefficients showed that both BIM and artificial intelligence had significant positive effects on environmental impact reduction, with BIM showing a slightly stronger standardized effect than AI. This result may reflect the current stage of digital transformation in construction projects, where BIM is more familiar and more widely implemented than AI. BIM has already been adopted in many design, coordination, and project management processes, while AI applications are still emerging and may be used selectively in specific tasks such as prediction, optimization, or monitoring. This finding is consistent with reviews showing that AI has strong potential in construction but still faces challenges related to implementation readiness, data availability, interoperability, and organizational adoption [8, 9, 12]. At the same time, the significant independent effect of AI confirms that AI is not merely an auxiliary tool but an emerging driver of environmental performance. The combined significance of BIM and AI indicates that sustainable construction management benefits from both structured digital modeling and intelligent data-driven analysis. This confirms the theoretical expectation that the future of construction sustainability depends on the integration of multiple digital technologies rather than reliance on one isolated platform.

The findings also showed that BIM application, artificial intelligence application, and environmental impact reduction significantly predicted sustainable construction management. Among these predictors, environmental impact reduction had the strongest effect, indicating that sustainable construction management is closely tied to the actual reduction of waste, emissions, energy consumption, material inefficiency, and rework. This result is conceptually important because it shows that sustainability in construction management should not be reduced to formal policies or general environmental intentions. Instead, it must be reflected in measurable improvements in project processes and environmental outcomes. The result aligns with research emphasizing that sustainable construction requires lifecycle-oriented, data-driven, and performance-based management systems [1, 15]. It is also consistent with studies on data-driven net-zero carbon monitoring, which argue that GIS, BIM, remote sensing, and AI can support more precise monitoring of sustainability indicators in buildings, infrastructure, and cities [19]. Therefore, the present findings support the view that environmental impact reduction acts as a key operational pathway through which digital technologies contribute to sustainable construction management.

The significant predictive effects of BIM and AI on sustainable construction management also support previous research on digital twins, smart buildings, and intelligent construction systems. Digital twins extend BIM by connecting digital models with real-time data, simulation, monitoring, and feedback mechanisms. When combined with AI, digital twins can support adaptive decision-making, predictive maintenance, energy optimization, environmental monitoring, and lifecycle sustainability analysis [15-17]. The findings of this study are consistent with this line of research because they show that digital technologies contribute to sustainable management not only by improving environmental indicators but also by strengthening managerial control and decision-making capacity. Studies on the sustainable integration of BIM and digital twin technologies in industrial infrastructure similarly emphasize that digital integration can improve sustainability when it is planned according to lifecycle principles and connected to operational performance data [18]. In addition, research on intelligent construction based on digital twins has shown that multidimensional models and interactive simulation can improve construction decision-making and system-level coordination [14]. These studies help explain why BIM and AI were significant predictors in the present research.

The results also have implications for broader urban and infrastructure sustainability. Construction projects are not isolated technical activities; they are embedded in urban systems, infrastructure networks, industrial areas, campuses, and smart city environments. The positive relationships found in this study are consistent with research indicating that digital twins, BIM, AI, IoT, remote sensing, and urban metabolism frameworks can help manage sustainability at larger scales [19-21]. Smart and green building technologies increasingly depend on the integration of AI and IoT to monitor environmental conditions, optimize energy use, and support sustainable building design [26]. Similarly, studies on smart cities and smart buildings argue that applied AI can become a key mechanism for achieving sustainability goals when digital systems are linked to environmental performance and governance processes [2]. The findings of the present study support this broader perspective by demonstrating that even at the project level, BIM and AI are associated with both environmental impact reduction and sustainable management capacity.

The findings can also be interpreted in relation to the broader shift toward Fourth Industrial Revolution and Industry 5.0 principles in engineering and construction. Contemporary construction management is moving from manual, fragmented, and reactive systems toward integrated, intelligent, automated, and human-centered systems. Prior research suggests that the Fourth Industrial Revolution is reshaping engineering through digital platforms, AI, automation, IoT, cloud systems, and advanced analytics [23]. At the same time, Industry 5.0 highlights sustainability, resilience, and human-centered technological development in construction [3]. The present results support this transition by showing that BIM and AI are not only technological innovations but also managerial resources for sustainable decision-making. However, the findings also imply that technology alone is insufficient. BIM and AI must be embedded in project workflows, professional competencies, organizational standards, sustainability targets, and decision-making routines. Research on generative AI in architectural engineering and AI-supported visualization similarly emphasizes both the potential and challenges of intelligent tools in design, communication, and stakeholder interaction [12, 24]. Therefore, sustainable construction management requires technological integration, organizational readiness, and professional interpretation.

Finally, the results are relevant to renovation, reconstruction, infrastructure modernization, and immersive digital collaboration. The significant effects of BIM and AI indicate that these technologies can support sustainability in contexts where project complexity, uncertainty, and resource constraints are high. Studies on the integration of BIM and artificial intelligence of things in reconstruction and renovation show that combined digital systems can improve monitoring, planning, and decision-making in complex building interventions [27]. Likewise, immersive technology combined with BIM can strengthen sustainable smart city planning, visualization, and collaborative decision-making [25]. In infrastructure and developing-country contexts, AI integration strategies have been shown to support smarter pavement engineering and more advanced infrastructure management [22]. These studies support the present findings by showing that the environmental value of BIM and AI extends across different construction domains. Overall, the findings confirm that BIM and artificial intelligence are significant technological and managerial enablers of environmental impact reduction and sustainable construction management.

This study had several limitations that should be considered when interpreting the findings. First, the study was conducted among construction professionals in Tehran, and although the sample included a diverse group of engineers, architects, project managers, BIM specialists, construction management experts, and environmental consultants, the findings may not be fully generalizable to other cities, regions, or countries with different construction regulations, technological infrastructures, organizational cultures, and sustainability requirements. Second, the study relied on self-reported questionnaire data, which may be influenced by respondents' perceptions, professional attitudes, or social desirability bias. Third, the research design was cross-sectional, meaning that the relationships among BIM, artificial intelligence, environmental impact reduction, and sustainable construction management were examined at one point in time. Therefore, causal conclusions should be made cautiously. Fourth, the study measured perceived use and perceived environmental contribution of BIM and AI rather than directly measuring actual energy savings, carbon reduction, waste reduction, or lifecycle environmental performance in completed construction projects.

Future studies should examine the role of BIM and artificial intelligence in sustainable construction management using longitudinal and project-based research designs. Such studies could follow construction projects from design to execution and operation in order to measure how BIM and AI affect actual environmental indicators over time. Future researchers should also compare different types of projects, such as residential buildings, commercial complexes, industrial facilities, road projects, infrastructure systems, and renovation projects, because the environmental effects and digital requirements of each project type may differ. In addition, future research could investigate mediating and moderating variables such as organizational readiness, digital skills, data quality, interoperability, project complexity, stakeholder collaboration, and regulatory support. Mixed-method studies are also recommended, because interviews with construction professionals can provide deeper insight into the barriers, practical challenges, and managerial conditions that influence the successful integration of BIM and AI in sustainable construction.

Based on the findings, construction companies, consulting firms, project managers, and policymakers should strengthen the integration of BIM and artificial intelligence into sustainable construction management processes. BIM should be used not only for modeling and visualization but also for environmental planning, material optimization, clash prevention, lifecycle assessment, and reduction of rework. AI tools should be gradually introduced for waste prediction, carbon emission analysis, energy performance evaluation, risk forecasting, resource optimization, and real-time site monitoring. Organizations should also invest in professional training so that engineers, architects, managers, and environmental specialists can interpret digital outputs and use them in practical decision-making. In addition, construction organizations should develop internal standards for data quality, model integration, sustainability indicators, and digital collaboration. The greatest practical benefit will be achieved when BIM and AI are not used as separate technologies but are integrated into a unified management system that supports environmental performance, cost control, schedule efficiency, and long-term sustainability.

Authors' Contributions

Authors equally contributed to this article.

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Declaration of Interest

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All procedures performed in this study were under the ethical standards.

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