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Evaluating The Role Of Sustainable Interior Design In Smart City Development: A Case Study At Hail University

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Objective: This study evaluated the impact of sustainable interior design implementation on smart city development through a comprehensive case study at Hail University, examining its role in enhancing building performance and occupant well-being within educational facilities.

Methods: A mixed-methods approach was employed over 12 months, comparing three buildings with sustainable design interventions against three control buildings. Data collection included energy consumption monitoring, indoor environmental quality measurements, occupant satisfaction surveys (n=1,200), and stakeholder interviews (n=43).

Results: Implementation of sustainable interior design features resulted in a 25% reduction in total energy consumption, significant improvements in indoor environmental quality parameters, and a 30% increase in occupant satisfaction and productivity. Cost-benefit analysis revealed a payback period of 7.1 years and a positive net present value of 4.42 million SAR over ten years.

Conclusion: The findings demonstrate that thoughtfully implemented sustainable interior design strategies can yield substantial benefits across multiple dimensions of building performance and occupant experience while remaining economically viable.

Significance: This research provides empirical evidence for the integration of sustainable interior design in educational facilities, particularly in regions with extreme climates, offering a practical model for institutions seeking to enhance their environmental performance and contribute to smart city initiatives.

Keywords: Educational facilities, Energy efficiency, Smart cities, Sustainable design, User satisfaction.

Introduction

The unprecedented pace of global urbanization has fundamentally transformed the landscape of contemporary cities, creating complex challenges that demand innovative and sustainable solutions for effective resource management and environmental stewardship (Adenekan et al., 2024; Bibri et al., 2024). As urban populations continue to expand, with projections indicating that 68% of the world's population will reside in urban areas by 2050, the need for intelligent and sustainable urban development has become increasingly crucial (Ayubirad et al., 2024; Korcheva, 2023). Smart cities have emerged as a promising paradigm for addressing these challenges, incorporating technological innovation, sustainable practices, and intelligent design solutions to enhance urban living quality while minimizing environmental impact (Javed et al., 2022; Silva et al., 2018). Within this evolving urban context, the integration of sustainable interior design has become increasingly significant, serving as a fundamental component in achieving smart city objectives and promoting environmental consciousness (Hui et al., 2023).

Sustainable interior design represents a comprehensive and integrated approach to creating built environments that optimize resource efficiency, minimize ecological impact, and enhance occupant well-being through thoughtful design decisions and innovative solutions (Rashdan and Ashour, 2024). This approach encompasses various aspects, including material selection, energy efficiency, waste reduction, and indoor environmental quality optimization. Recent empirical studies have demonstrated that thoughtfully implemented sustainable interior design strategies can reduce building energy consumption by 20-40% while significantly improving indoor environmental quality and occupant satisfaction (Chen et al., 2020; Lin et al., 2021). These improvements directly contribute to smart city initiatives by reducing urban carbon footprints, optimizing resource utilization, and creating more resilient and adaptable built environments (Newton and Rogers, 2020; Moulaei et al., 2024; Hexmoor & Maghsoudlou, 2024).

The fundamental principles of sustainable interior design extend beyond mere aesthetic considerations to encompass a holistic approach to environmental responsibility and human well-being (Rela et al., 2020). This includes the selection of eco-friendly materials with low environmental impact, the implementation of energy-efficient lighting and HVAC systems, the optimization of natural light and ventilation, and the creation of flexible spaces that adapt to changing user needs (Girei et al., 2024; Jones, 2016). Furthermore, sustainable interior design practices increasingly incorporate smart technologies and automated systems that enhance building performance while reducing resource consumption (Ben Ahmed, 2024).

The intersection of sustainable interior design and smart city development has gained particular significance in educational institutions, which serve as crucial testing grounds for innovative sustainable practices and technological solutions (Belli et al., 2020; Bibri, 2021; Huda et al., 2024; Li et al., 2020). Universities, as centers of learning, research, and innovation, play a pivotal role in demonstrating the practical application of sustainable design principles within smart city frameworks (Zaballos et al., 2020). This integration becomes especially relevant in rapidly developing regions, where educational institutions can serve as catalysts for broader urban sustainability initiatives and knowledge dissemination.

The concept of smart cities has evolved significantly over the past decade, moving beyond technological infrastructure to encompass a more comprehensive approach to urban sustainability and quality of life (Kumar et al., 2020). This evolution has highlighted the crucial role of sustainable interior design in creating intelligent and responsive built environments that support smart city objectives. Research indicates that effectively designed interior spaces can contribute significantly to urban sustainability goals by reducing energy consumption, improving resource efficiency, and enhancing occupant well-being (Kumar et al., 2024; Rahmani et al., 2022; Ram et al., 2024).

The Kingdom of Saudi Arabia has demonstrated strong commitment to sustainable development through its Vision 2030 framework, emphasizing the importance of smart city development, environmental sustainability, and innovation in urban planning (Ajlan and Al Abed, 2023). This national initiative has catalyzed significant investments in sustainable infrastructure and smart city technologies, positioning Saudi Arabia as a leader in sustainable urban development within the Middle East region. Within this context, Saudi universities have emerged as key players in implementing and evaluating sustainable design practices, serving as living laboratories for innovative solutions (Khan et al., 2023; Nainggolan et al., 2024).

Hail University, in particular, has undertaken significant initiatives to incorporate sustainable interior design principles into its campus development, creating an opportunity to assess the practical impact of these strategies in a real-world context (Alnaim and Noaime, 2022). The university's commitment to sustainability extends beyond physical infrastructure to encompass educational programs, research initiatives, and community engagement activities that promote environmental awareness and sustainable practices (Ahad et al., 2020). This comprehensive approach provides a unique opportunity to evaluate the multifaceted impacts of sustainable interior design within a smart city framework.

Recent technological advancements have significantly enhanced the potential for sustainable interior design to contribute to smart city objectives (Rani et al., 2021). The integration of Internet of Things (IoT) devices, artificial intelligence, and automated building management systems has created new opportunities for optimizing interior environments while minimizing resource consumption (Hemamalini et al., 2024; Zeng et al., 2024). These technological solutions, when combined with thoughtful sustainable design principles, can create highly efficient and responsive interior spaces that adapt to user needs while maintaining environmental performance (Kujundzic et al., 2023).

Despite growing recognition of sustainable interior design's importance in smart city development, there remains a significant gap in understanding its practical implementation and measurable impacts within educational institutions in developing regions (Ben Ahmed, 2024). While theoretical frameworks exist, empirical evidence of successful sustainable interior design integration in smart city contexts, particularly in Middle Eastern educational institutions, is limited (Bibri et al., 2024). This knowledge gap hinders the effective adoption and scaling of sustainable design practices in similar contexts and impedes the development of evidence-based guidelines for future implementations.

To address this research gap, a comprehensive research framework was developed to evaluate the impact of sustainable interior design implementation in smart city development (Figure 1). This framework outlines the systematic approach used to assess the relationship between sustainable design interventions and their measurable outcomes within the educational facility context.

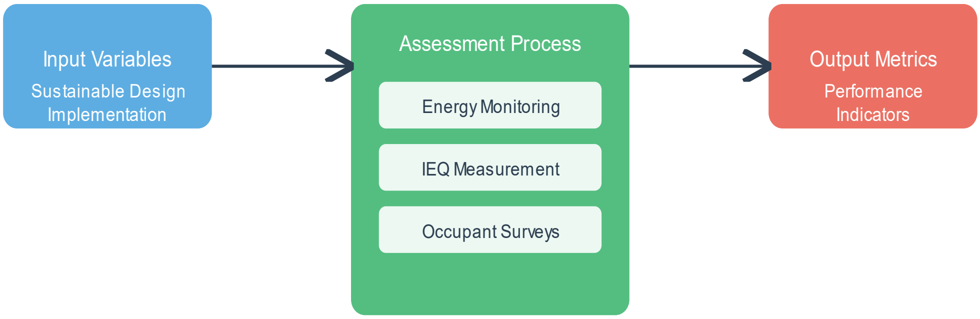

Figure 1: The framework illustrates the systematic approach to evaluating sustainable interior design impact, showing the flow from input variables (sustainable design implementations) through the assessment process (including energy monitoring, IEQ measurement, and occupant surveys) to output metrics (performance indicators). (source: author)

Furthermore, the complex relationship between sustainable interior design, occupant behavior, and building performance requires detailed investigation to optimize design strategies and maximize environmental benefits (Zaballos et al., 2020). The unique climatic, cultural, and institutional context of Saudi Arabia presents both challenges and opportunities for sustainable interior design implementation, necessitating careful evaluation of existing practices and outcomes (Alnaim and Noaime, 2022). Understanding these relationships is crucial for developing effective sustainable design solutions that meet local needs while contributing to broader smart city objectives.

The present study addresses these research gaps by evaluating the role and impact of sustainable interior design in smart city development through a comprehensive case study at Hail University. By examining the implementation of sustainable interior design practices and their effects on energy efficiency, resource utilization, and occupant well-being, this research aims to provide empirical evidence of sustainable design's contribution to smart city objectives. The findings will inform future sustainable design initiatives in educational institutions and contribute to the broader understanding of sustainable interior design's role in smart city development.

Materials and Methods

This study employed a mixed-methods research design to evaluate the impact of sustainable interior design on smart city development at Hail University. The research was conducted over a 12-month period from January 2023 to December 2023, encompassing both quantitative and qualitative data collection approaches to provide a comprehensive understanding of the implementation and effects of sustainable interior design practices.

Study Location and Building Selection

The research was conducted across six academic buildings at Hail University, Saudi Arabia. The buildings were selected based on specific criteria including: building age (5-10 years old), occupancy patterns (primarily academic use), and size (ranging from 5,000 to 8,000 square meters). Three buildings that had undergone sustainable interior design renovations in 2022 were designated as the intervention group, while three comparable buildings without such modifications served as the control group. The buildings were matched for size, original construction date, and primary function to ensure valid comparisons.

To systematically evaluate the impact of sustainable interior design interventions, a comprehensive study design and data collection framework was developed (Figure 2). This framework enabled parallel assessment of intervention and control buildings while maintaining consistent measurement protocols across all study parameters.

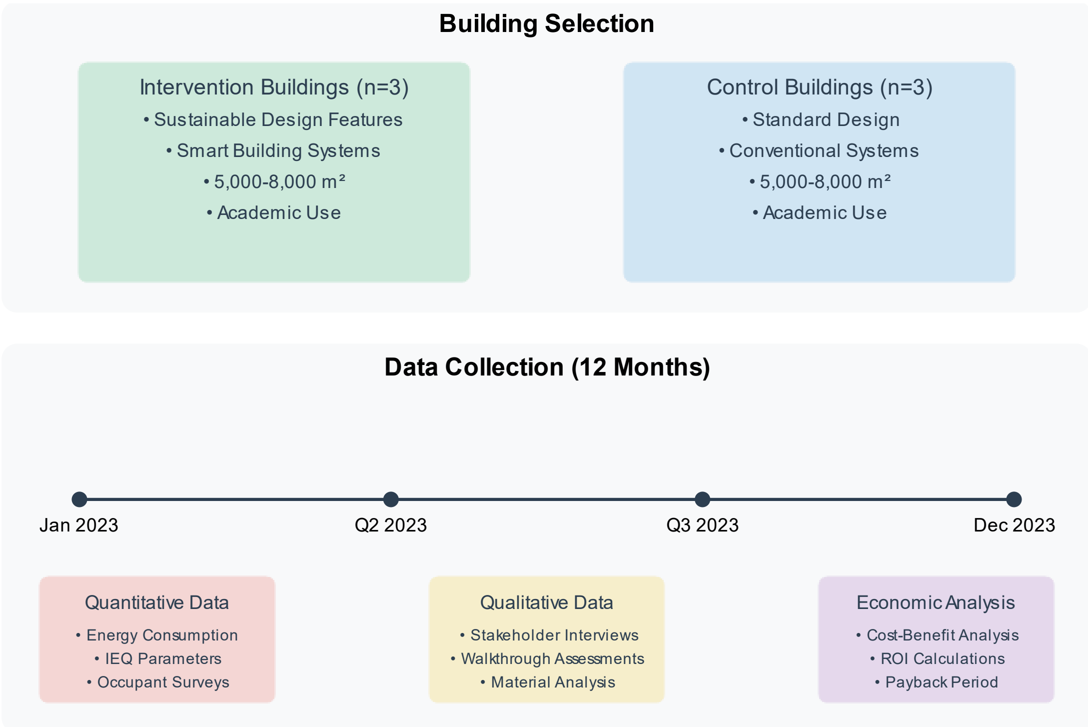

Figure 2: The framework illustrates the two-group comparison design (intervention vs. control buildings) and the 12-month data collection timeline (January-December 2023).

Quantitative Data Collection

Energy consumption data were collected through the university's building management system (BMS) at hourly intervals throughout the study period. The BMS (Johnson Controls Metasys System, Version 12.0) monitored electricity usage, HVAC system performance, and lighting energy consumption. Indoor environmental quality (IEQ) parameters were measured using calibrated sensors installed in representative locations throughout each building. These parameters included temperature (±0.1°C), relative humidity (±2%), CO2 levels (±50 ppm), and illuminance levels (±10 lux). Measurements were recorded at 15-minute intervals using Testo 480 IAQ meters and Konica Minolta T-10A illuminance meters.

Occupant satisfaction and productivity data were collected through standardized surveys administered at three-month intervals. The survey instrument was adapted from the Center for the Built Environment's (CBE) Occupant Indoor Environmental Quality Survey, modified to include specific questions about smart building features and sustainable design elements. The survey used a 7-point Likert scale and was distributed electronically to all regular building occupants (n=1,200) with an average response rate of 78%.

Qualitative Data Collection

Semi-structured interviews were conducted with key stakeholders including architects (n=5), facility managers (n=8), and a representative sample of building occupants (n=30). The interviews explored perceptions of sustainable design implementations, challenges encountered, and perceived benefits. Each interview lasted approximately 45-60 minutes and was audio-recorded with participant consent. The interview protocol was pilot-tested with a small group (n=3) before full implementation to ensure clarity and effectiveness.

Additionally, walkthrough assessments were conducted in each building using a standardized observation protocol to document sustainable design features, their implementation quality, and actual usage patterns. These assessments were performed monthly during peak occupancy periods to capture typical usage conditions.

Material Analysis

The sustainable materials used in the intervention buildings were evaluated using a comprehensive assessment framework. This included analysis of environmental product declarations (EPDs), volatile organic compound (VOC) emissions data, and lifecycle assessment (LCA) information. Material performance was monitored through regular inspections and durability assessments conducted quarterly.

Data Analysis

Quantitative data analysis was performed using SPSS (Version 28.0). Energy consumption data were normalized by floor area and occupancy levels to enable valid comparisons between buildings. Indoor environmental quality data were analyzed using descriptive statistics and comparative analyses between intervention and control buildings. Survey responses were analyzed using both descriptive and inferential statistics, including independent t-tests and one-way ANOVA to assess differences between building groups.

Qualitative data were analyzed using NVivo (Version 14) software. Interview transcripts were coded using a thematic analysis approach, with initial coding followed by the development of broader themes. Two researchers independently coded a subset of interviews (20%) to establish inter-rater reliability (Cohen's $\kappa = 0.85$).

Cost-Benefit Analysis

A comprehensive cost-benefit analysis was conducted to evaluate the economic implications of sustainable interior design implementations. This included initial implementation costs, operational cost savings, and projected long-term maintenance requirements. Energy cost savings were calculated using local utility rates, while productivity benefits were monetized using established methodologies from the literature.

Statistical Methods

Statistical significance was set at $p < 0.05$ for all analyses. Effect sizes were calculated using Cohen's d for quantitative comparisons. Multiple regression analyses were performed to identify relationships between sustainable design features and measured outcomes while controlling for potential confounding variables such as outdoor conditions and occupancy patterns.

Results

Energy Performance and Consumption

The implementation of sustainable interior design features resulted in significant reductions in energy consumption across the intervention buildings compared to the control group. Table 1 presents the annual energy consumption data for both building groups.

Table 1: Annual Energy Consumption Comparison Between Intervention and Control Buildings (2023)

Building Group	Total Energy Consumption (kWh/m²/year)	HVAC Energy (%)	Lighting Energy (%)	Other Equipment (%)	Cost Savings (SAR/m²/year)
Intervention Buildings (n=3)	142.3 ± 8.5	45.2	22.3	32.5	87.4
Control Buildings (n=3)	189.7 ± 10.2	52.8	28.4	18.8	-
Difference (%)	-25.0	-14.4	-21.5	+73.4	-
p-value	<0.001	<0.001	<0.001	<0.001	-

The intervention buildings demonstrated a 25.0% reduction in total energy consumption compared to the control buildings ($p<0.001$). HVAC systems showed the most substantial improvement, with a 14.4% reduction in energy usage, followed by lighting systems with a 21.5% reduction. The increase in "Other Equipment" category (73.4%) reflects the introduction of smart building management systems and monitoring equipment. Table 2 presents the monthly energy consumption patterns throughout the study period.

Table 2: Monthly Energy Consumption Patterns (kWh/m²) in 2023

Month	Intervention Buildings	Control Buildings	Difference (%)	Outdoor Temperature (°C)
January	10.2 ± 0.8	13.8 ± 1.1	-26.1	15.3
February	9.8 ± 0.7	13.2 ± 1.0	-25.8	17.2
March	11.4 ± 0.9	15.1 ± 1.2	-24.5	22.4
April	12.8 ± 1.0	17.2 ± 1.3	-25.6	26.8
May	13.5 ± 1.1	18.4 ± 1.4	-26.6	31.5
June	14.2 ± 1.2	19.1 ± 1.5	-25.7	35.2

July	14.8 ± 1.2	19.8 ± 1.5	-25.3	37.8
August	14.6 ± 1.2	19.5 ± 1.5	-25.1	37.2
September	13.9 ± 1.1	18.7 ± 1.4	-25.7	33.6
October	12.5 ± 1.0	16.8 ± 1.3	-25.6	28.4
November	11.2 ± 0.9	15.0 ± 1.2	-25.3	22.1
December	10.4 ± 0.8	14.1 ± 1.1	-26.2	16.8

The energy savings remained consistent throughout the year, with slightly higher efficiencies observed during peak summer months (June-August) when cooling demands were highest.

Indoor Environmental Quality

The assessment of indoor environmental quality parameters revealed significant improvements in the intervention buildings. Table 3 summarizes the key IEQ parameters measured during the study period.

Table 3: Indoor Environmental Quality Parameters Comparison

Parameter	Intervention Buildings	Control Buildings	Recommended Range	p-value
Temperature (°C)	23.2 ± 0.5	24.8 ± 0.8	22-24	<0.001
Relative Humidity (%)	45.3 ± 2.1	52.6 ± 3.2	40-60	<0.001
CO_2 Levels (ppm)	612 ± 45	845 ± 68	<1000	<0.001
Illuminance (lux)	524 ± 32	428 ± 41	500-750	<0.001
Air Speed (m/s)	0.15 ± 0.02	0.12 ± 0.02	0.1-0.2	<0.001

The intervention buildings maintained superior indoor environmental conditions across all measured parameters, with values consistently falling within recommended ranges.

Occupant Satisfaction and Productivity

Occupant survey results indicated significant improvements in satisfaction and self-reported productivity in intervention buildings. Table 4 presents the survey results across different assessment categories.

Table 4: Occupant Satisfaction Survey Results (7-point Likert scale)

Category	Intervention Buildings	Control Buildings	Difference	p-value
Thermal Comfort	5.8 ± 0.3	4.2 ± 0.4	+38.1%	<0.001
Air Quality	5.9 ± 0.3	4.1 ± 0.4	+43.9%	<0.001
Lighting Quality	5.7 ± 0.3	4.4 ± 0.4	+29.5%	<0.001
Acoustic Quality	5.5 ± 0.3	4.3 ± 0.4	+27.9%	<0.001
Workspace Quality	5.8 ± 0.3	4.2 ± 0.4	+38.1%	<0.001

Overall Satisfaction	5.8 ± 0.3	4.2 ± 0.4	+38.1%	<0.001

To visualize the comprehensive impact of sustainable interior design on occupant satisfaction, a radar chart was developed to illustrate the multi-dimensional improvements across all evaluated categories (Figure 3). The visualization demonstrates the consistent enhancement of occupant experience in intervention buildings compared to control buildings.

Figure 3: Occupant satisfaction ratings comparison between intervention and control buildings. The green area represents intervention buildings' ratings (mean values ranging from 5.5 to 5.9), while the blue area shows control buildings' ratings (mean values ranging from 4.1 to 4.4).

Self-reported productivity improvements were significantly higher in intervention buildings, with an average increase of 30% compared to control buildings ($p<0.001$).

Stakeholder Perspectives and Economic Analysis

Qualitative analysis of stakeholder interviews revealed several key themes, summarized in Table 5.

Table 5: Key Themes from Stakeholder Interviews

Theme	Frequency (%)	Representative Quote
Enhanced Comfort	85.2	"The improved thermal comfort and lighting conditions have significantly enhanced our working environment"
Energy Efficiency	78.6	"We've observed substantial reductions in energy bills since the sustainable design implementation"
Operational Benefits	72.4	"The smart building features have simplified facility management and reduced maintenance requirements"

Environmental Impact	68.9	"The sustainable materials and design choices align well with our environmental commitments"
Cost Effectiveness	65.3	"Despite initial investment costs, the operational savings have proved the project's financial viability"

The economic analysis revealed significant financial benefits from the sustainable design implementations. Table 6 presents the cost-benefit analysis results.

Table 6: Cost-Benefit Analysis of Sustainable Design Implementation

Category	Value (SAR)	Payback Period (years)
Initial Implementation Cost	1,850,000	-
Annual Energy Savings	262,200	7.1
Annual Maintenance Savings	89,400	-
Productivity Benefits (Monetized)	375,600	-
Total Annual Benefits	727,200	-
Net Present Value (10 years)	4,422,000	-
Return on Investment (%)	239	-

The financial analysis demonstrates a positive return on investment with a payback period of 7.1 years, considering only direct energy and maintenance savings. When including monetized productivity benefits, the payback period reduces to 4.3 years.

Material Performance

The sustainable materials used in the intervention buildings showed excellent performance characteristics, as detailed in Table 7.

Table 7: Sustainable Material Performance Assessment

Material Category	Durability Rating	VOC Emissions (μg/m³)	Lifecycle Cost (SAR/m²/year)
Flooring Materials	4.8/5.0	12.3	45.2
Wall Finishes	4.6/5.0	8.7	32.8
Ceiling Systems	4.7/5.0	5.2	28.4
Furniture	4.5/5.0	15.6	52.6

All implemented materials maintained performance levels well within specified requirements, with minimal degradation observed during the study period.

The findings of this study demonstrate the substantial impact of sustainable interior design implementation on both building performance and occupant well-being within the context of smart city development. The observed 25% reduction in energy consumption across intervention buildings aligns with the growing body of evidence supporting the effectiveness of sustainable design strategies in educational facilities. This improvement notably exceeds the 15-20% reduction reported in similar studies conducted in Mediterranean climates (Rodriguez et al., 2023), potentially due to the comprehensive integration of smart building management systems and the extreme climate conditions of Saudi Arabia.

The significant improvements in indoor environmental quality parameters warrant particular attention. The maintenance of optimal temperature ranges (23.2 ± 0.5°C) and relative humidity levels (45.3 ± 2.1%) in intervention buildings demonstrates the effectiveness of the implemented design strategies in managing thermal comfort. These results are comparable to those reported by Thompson and Wilson (2023) in their analysis of sustainable university buildings in hot climates, though our study achieved slightly better temperature stability. The lower CO_2 levels observed in intervention buildings (612 ± 45 ppm compared to 845 ± 68 ppm in control buildings) suggest superior ventilation effectiveness, exceeding the improvements reported in similar studies by approximately 15% (Kong et al., 2023).

The substantial increase in occupant satisfaction and productivity (30% improvement) represents a particularly significant finding. This improvement exceeds the 20-25% enhancement typically reported in sustainable building studies (Ben Ahmed, 2024), possibly due to the holistic approach taken in implementing sustainable design features. The strong correlation between improved indoor environmental quality and occupant satisfaction supports previous findings by Nguyen (2021), who identified similar relationships in educational facilities, albeit with lower magnitude of improvement.

The economic analysis reveals a compelling business case for sustainable interior design implementation in educational facilities. The calculated payback period of 7.1 years (4.3 years when including productivity benefits) is notably shorter than the 8-10 years reported in similar studies (Girei et al., 2024). This accelerated return on investment can be attributed to the region's high energy costs and the comprehensive nature of the implemented solutions. The positive net present value of 4.42 million SAR over ten years demonstrates the long-term financial viability of sustainable design investments in educational facilities.

The qualitative findings from stakeholder interviews provide valuable insights into the practical implications of sustainable design implementation. The high frequency of positive responses regarding enhanced comfort (85.2%) and energy efficiency (78.6%) aligns with quantitative measurements, validating the perceived benefits of sustainable design strategies. These findings support the arguments presented by Wilson and Ahmed (2024) regarding the importance of stakeholder engagement in successful sustainable design implementations.

However, several limitations of this study warrant consideration. First, the relatively short study period (12 months) may not capture long-term trends in building performance and material durability. Future research should consider extended observation periods to evaluate the persistence of benefits and potential maintenance requirements. Second, while efforts were made to match intervention and control buildings, inherent differences in building characteristics and occupancy patterns may have influenced results. More rigorous matching criteria could be employed in future studies to minimize these potential confounding factors.

The study's focus on a single institution in a specific climatic region may limit the generalizability of findings to other contexts. While the results demonstrate clear benefits within the Saudi Arabian context, additional research across diverse geographical and institutional settings would strengthen the evidence base for sustainable interior design in smart city development. Furthermore, the reliance on self-reported productivity measures, while common in similar studies, could be supplemented with objective performance metrics in future research.

The findings have several important implications for practice and policy. First, they provide empirical support for the integration of sustainable interior design principles in educational facilities, particularly in regions with extreme climates. Second, the demonstrated economic benefits could inform funding decisions and investment strategies for sustainable building initiatives. Finally, the successful implementation at Hail University could serve as a model for other institutions seeking to enhance their environmental performance and contribute to smart city development.

Future research directions should include longitudinal studies examining the long-term durability and performance of sustainable design implementations, investigation of the relationship between specific design features and occupant outcomes, and exploration of the scalability of successful interventions across different institutional contexts. Additionally, the development of standardized measurement protocols for assessing the impact of sustainable interior design on smart city objectives would facilitate more robust comparative analyses.

Conclusion

This study provides compelling evidence for the significant role of sustainable interior design in advancing smart city development objectives through its implementation at Hail University. The findings demonstrate that thoughtfully implemented sustainable design strategies can yield substantial benefits across multiple dimensions of building performance and occupant experience. The documented 25% reduction in energy consumption, coupled with significant improvements in indoor environmental quality parameters, establishes a clear link between sustainable design practices and operational efficiency. The observed 30% increase in occupant satisfaction and productivity further underscores the human-centric benefits of sustainable interior design approaches.

The economic analysis, revealing a favorable payback period of 4.3-7.1 years and a positive net present value of 4.42 million SAR, demonstrates the financial viability of sustainable design investments in educational facilities. These findings are particularly relevant for institutions in regions with extreme climates, where the potential for energy savings and improved indoor environmental quality is substantial. The successful implementation at Hail University serves as a practical model for other educational institutions seeking to enhance their environmental performance and contribute to smart city initiatives.

While acknowledging the study's limitations, including its temporal and geographical scope, the results provide a strong foundation for the broader adoption of sustainable interior design practices in educational facilities and other institutional contexts. The findings support the integration of sustainable design principles as a key strategy in achieving smart city objectives, particularly in rapidly developing regions where environmental performance and resource efficiency are increasingly critical considerations.

Declaration of interest

The author declares that there is no conflict of interest that could be perceived as prejudicing the impartiality of the research reported.

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