Integrating Biophilic Environmental Design and Fourth Industrial Revolution Technologies for Sustainable Economic Development: A Systematic Review of Residential Architecture

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ABSTRACT

The residential building sector is a critical driver of global sustainability due to its substantial resource consumption, energy demand, impact on human wellbeing, and economic productivity. Biophilic environmental design, which reconnects occupants with natural systems, has been shown to improve indoor environmental quality (IEQ), psychological well-being, and energy performance. Conversely, smart sensors, artificial intelligence (AI), Internet of Things (IoT), and data-driven building management, which are systems of Fourth Industrial Revolution (4IR) technologies, can optimise operational efficiency and adaptive building performance. Despite their individual merits, the integration of biophilic design with 4IR technologies remains underexplored, while the evidence on their combined environmental and economic outcomes has remained fragmented. A systematic review methodology, as guided by PRISMA, was adopted to coalesce empirical and theoretical evidence published between 2010 and 2025. Relevant peer-reviewed journals, conference papers, and grey literature were retrieved from Scopus, Web of Science, Google Scholar, and ScienceDirect using thematic concepts such as “biophilic design,” “4IR technologies,” “smart residential buildings,” and “sustainability.” Inclusion criteria focused on studies that reported environmental and economic outcomes related to residential architecture. Seventy-seven studies that met the inclusion criteria were examined using a Structured Data Extraction Matrix (SDEM). Findings indicate that biophilic/4IR-integrated residential buildings enhance IEQ, thermal comfort, and occupant wellbeing, while optimising energy efficiency, reducing operational costs, and lowering carbon emissions. Comparative and thematic analyses show that these buildings outperform conventional designs in environmental and economic performance and occupant satisfaction. The study recommends that architects, developers, and policymakers focus on integrating biophilic principles with 4IR technologies to achieve sustainable, human-centred residential design. Further empirical research is needed to assess the long-term economic impacts, cost-effectiveness, and policy integration of place-based and data-driven sustainable residential development.

Keywords: Biophilic Environmental Design, Fourth Industrial Revolution, PRISMA, Residential Architecture, Structured Data Extraction Matrix.

INTRODUCTION

The built environment sector that is focused on residential buildings has continued to be the major contributor to global sustainability challenges (Anderson, 2015; Wu & Skye, 2021; Yupeng & Chuanglin, 2023). Such challenges account for notable proportions of material use, energy consumption, waste generation, and carbon emissions. Fast-paced citification, a spike in population, and altering lifestyles of these populations have increased pressure on housing systems, especially as it concerns emerging and developing economies (Seto et al., 2012). Beyond the impact of environmental issues, poorly planned residential locales influence the well-being of occupants, indoor environmental quality (IEQ), long-term economic performance, and productivity (Al Horr, et al., 2016). Since the housing sector forms the foundational constituent of burghal economies, residential architecture, as part of that sector, performs a vital function in moulding economic development (Arku, 2010). This is achieved by influencing costs in public health, productivity of residents, and energy expenditure. To this end, there is an increasing persuasion in architectural approaches that are targeted to improve human wellbeing, environmental performance, and economic value.

As submitted by Söderlund & Newman (2015), Biophilic Environmental Design (BED) is a paradigm that is founded on the conviction that human beings possess an affinity for the innate. This is referred to as the biophilia hypothesis (Gaekwad et al., 2022). In the architecture of residential settlements, biophilic design has progressed from mere incorporation of greenery to the holistic integration of natural systems, materials, processes, and patterns within the built environment. Core principles include daylighting, natural ventilation, adoption of natural materials, non-visual and visual links to nature, and spatial configurations that imitate innate environments (Zhong et al., 2021). Data-driven studies, including Asojo & Hazazi (2025), Zhong et al. (2021), Jie et al. (2018), Al Sayyed (2025), and Sara et al. (2021), have connected biophilic residential environments to improvements in IEQ, enhanced visual and thermal comfort, upscaled cognitive performance, reduced levels of stress, and increased satisfaction of occupants. Ding et al. (2024), Nitu et al. (2022), Kalu et al. (2025), and Perini et al. (2025) provided significant insights into BEDs. They submit that BEDs reduce dependence on mechanical cooling networks, regulate the microclimate, and save costs on energy usage at the environmental scale. These contributions support the goals of sustainability on a wider scale (Söderlund & Newman, 2015).

4IR technologies are gradually changing the way buildings are planned and operated. Technologies such as smart sensors, artificial intelligence (AI), the Internet of Things (IoT), and empirical building management systems can optimise building performance, facilitate predictive control, and enable live tracking (Mahmoud et al., 2021; Mukilan et al., 2024). With respect to residential buildings, these digital instruments support energy efficiency through intelligent management of energy, smart lighting, automated ventilation, and occupancy-driven controls (Mukilan et al., 2024, and Das, 2025). Beyond energy performance, 4IR technologies reduce the costs of maintenance, improve operational efficiency, and enable occupant-centred control of indoor environments (Chinwe et al., 2025). Their ability to provide and examine bulk data makes them appropriate tools for making evidence-based decisions in sustainable housing delivery.

Inasmuch as BEDs and 4IR technologies have demonstrated gains when applied independently, existing studies of these constructs remain fragmented due to the limited synthesis of the duo's approaches. While several studies, such as Zhong et al. (2021), Yu et al. (2023), Abimbola & Fullah (2025), Al Sayyed (2025), and Zulnoorain et al. (2025), focus on either well-being and environmental outcomes of biophilic design, others, such as Qayyum et al. (2024), Chinedu et al. (2025), Puji et al. (2024), and Das (2025), revolve around energy efficiency and technological gains of smart residential systems. As opined by Tekin & Montelli (2025), Abdullah (2024), Zainab & Doğa (2025), and Tarek & Ouf (2021), the combined user-centred, environmental, and economic implications of integrating BED with 4IR technologies remain grossly understudied. At the end of the day, there is insufficient empirical evidence and knowledge on how such integration affects cost-efficiency, sustainable development results, and long-term economic productivity in residential architecture.

Aim and Objectives

This study aims to methodically review and synthesise subsisting literatures that revolve around the integration of BED and 4IR technologies in residential architecture, with a priority on sustainable economic development outcomes.

To this end, the following objectives, founded on the PICO framework, suffice:

1. Identify BED strategies deployed in residential buildings and their concomitant human-centred and environmental outcomes,
2. Examine the implementation of 4IR technologies in residential architecture and their contributions to operational performance and energy efficiency.
3. Analyse data on integrated biophilic/4IR strategies on occupant wellness, economic outcomes, and environmental performance, and
4. Define limitations, lacunae, and future study routes towards advancing integrated sustainable residential design.

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Significance of the Study

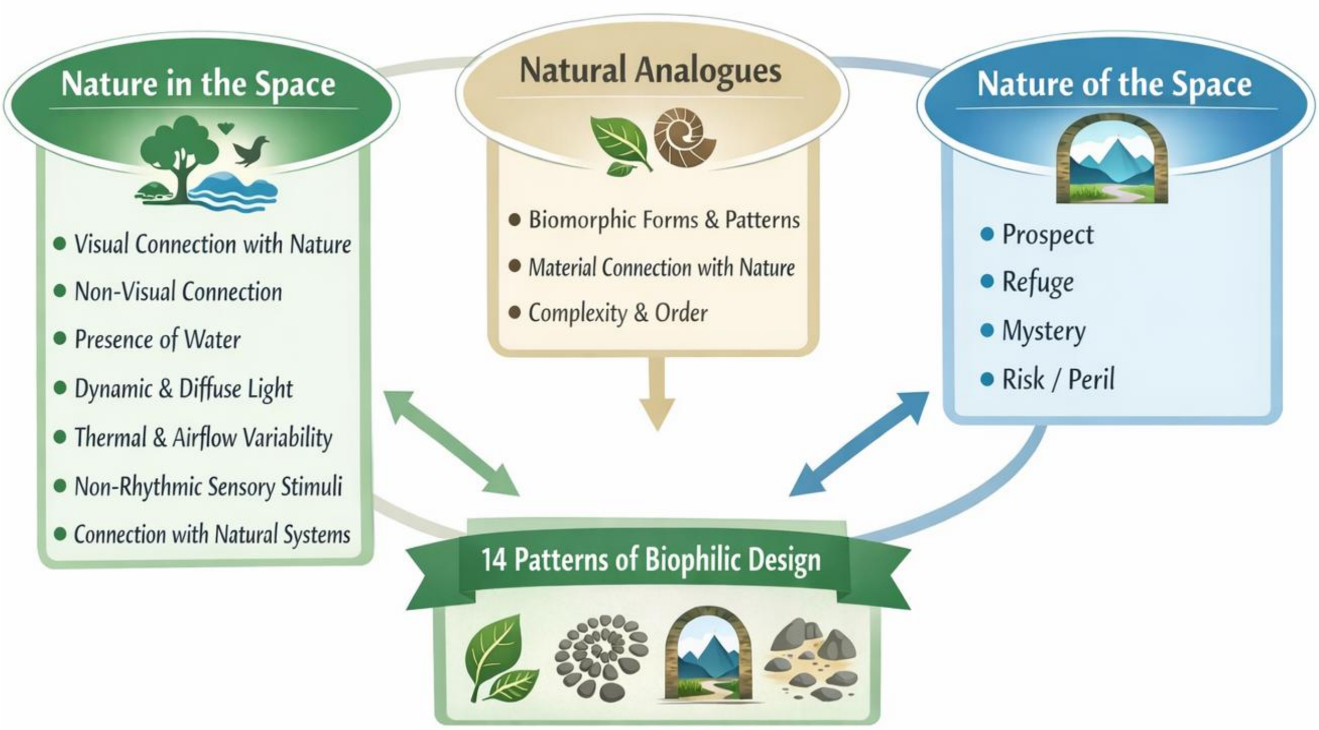
The study allows a contribution to architectural theory by way of advancing a synthesised and conceptual understanding of innate-founded planning and digitalisation in housing. For practice, it provided data-based insights to guide professionals in the built environment in the design of residential settlements that must enhance the well-being of their occupants while offering environmental and economic value. From the perspective of policy, outcomes of the study will support the evolution of innovative solutions and sustainable guidelines for housing and investment approaches that will be in tandem with sustainable economic development objectives.

CONCEPTUAL AND THEORETICAL FRAMEWORKS

BED Framework

The Biophilic Environmental Design (BED) framework is founded on the Biophilia Hypothesis as posited by Gaekwad et al. (2022) and Vanessa & Melinda (2023). Their works assert that human beings have an inherent tendency to satisfy an urge to connect with innate systems. This hypothesis, in architectural narratives, has evolved into organised biophilic templates that translate human-nature associations into sensory, material, and spatial design strategies. In residential architecture, BED frameworks are structured into three interlinked typologies, viz, Nature in the Space, Natural Analogues, and Nature of the Space (William et al., 2014).

Figure 1. The BED Framework



Note. The BED framework illustrates the three interlinked typologies in residential architecture. Source: Authors' workstation as recreated from William et al. (2014).

Nature in the Space seeks to address how close nature is and the level of its contact with a place or space. Zhong et al. (2021) list elements that exemplify 'Nature in the Space'. They include presence and contact with plants, animals, water, breeze, sounds, and olfactory stimuli from natural matter. Nature in the Space is felt more when occupants have a strong sensory bond to natural elements. This could be through multi-sensory interactions, movement, and diversity (Jie et al., 2024). Identifiable BED patterns seen under this typology include (1) Visual connection with nature, (2) Non-visual connection with nature, (3). Non-rhythmic sensory stimuli (4). Thermal and airflow variability (5). Presence of water (6). Dynamic and diffuse light, and (7). Connection with natural systems (William et al., 2014). Natural Analogues concern indirect evocations of nature (Asojo & Hazazi, 2025).

Such natural elements could be non-living. This is seen in the adoption of innate concepts, materials, their complexity, and order in the design and planning of habitations.

When natural materials, objects, colours, shapes, sequences, and patterns are adopted in an organised, evolving manner in design, such a process is observed to align with natural analogues (William et al., 2014). This typology features BED patterns like: (8) Biomorphic forms and patterns, (9). Material connection with nature (10). Complexity and order (Ghaziani, 2021).

The Nature of the Space helps users appreciate vistas beyond their immediate surroundings. It draws them to fascinations, slightly dangerous locales, obscured views, and revelatory moments (Tekin & Montelli, 2025).

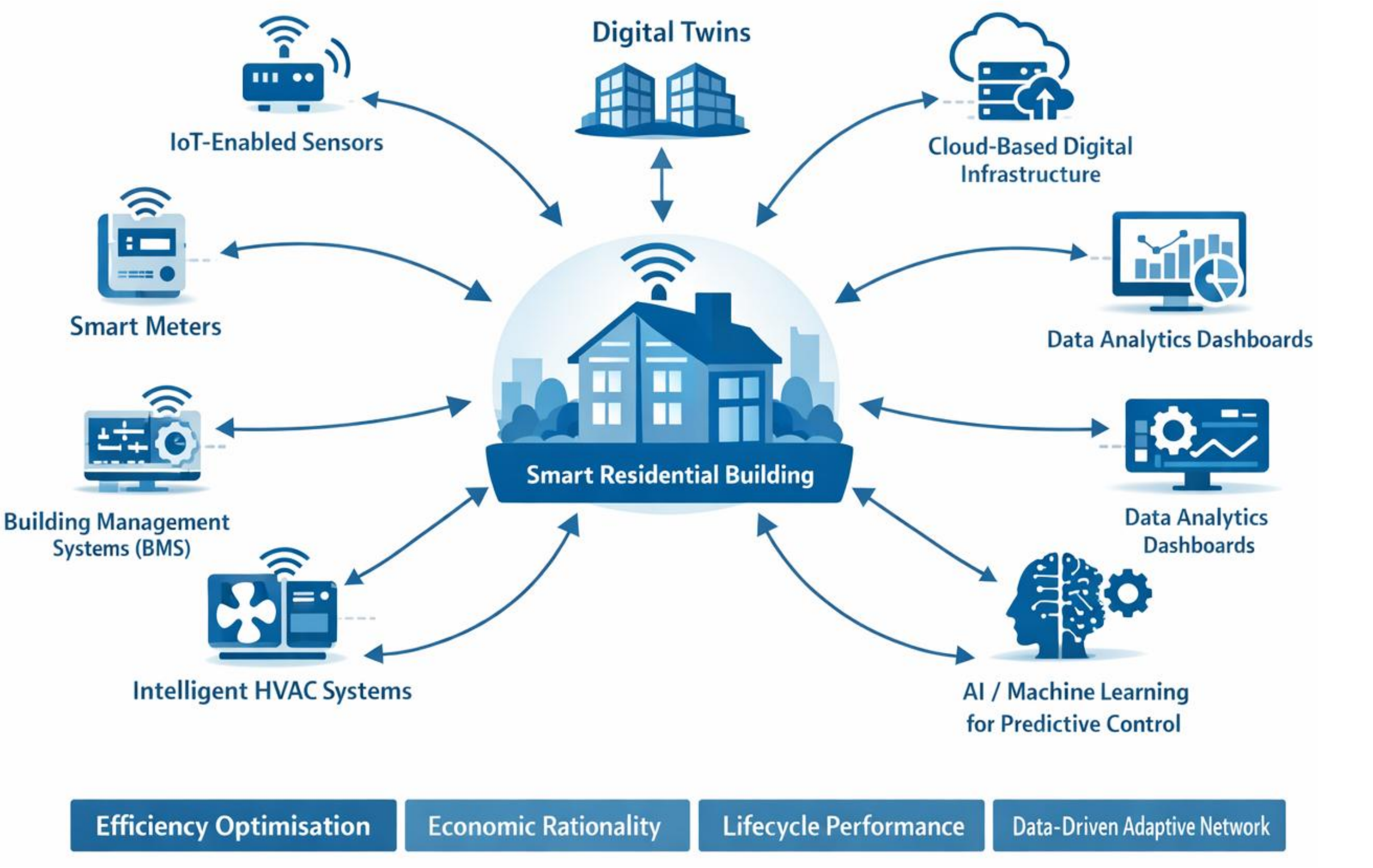
The strongest Nature of the Space perception is significant when spatial entities, retrofitted with Nature in the Space, are commingled with Natural Analogues (Ismail, 2021).

Observable BED patterns seen in this typology include: (11) Prospect, (12) Refuge, (13). Mystery, (14). Risk or Peril. A conglomeration of all the above-mentioned patterns constitutes the 14 Patterns of Biophilic Design (William et al., 2014).

Fourth Industrial Revolution Technologies (4IR) Framework

As opined by Sascha et al. (2022), Hansong et al. (2022), and Hana & Mario (2021), the framework for the Fourth Industrial Revolution is founded on the concepts of digital infrastructure and smart building ecosystems. In the discourse of residential architecture, the 4IR framework presents habitable structures as data-driven and adaptive networks that have the capability of sensing, analysing, and providing responses to environmental conditions and behaviours of occupants (Adrian et al., 2024).

Figure 2. 4IR Framework in Residential Architecture



Notes. An illustration of the 4IR framework showing IoT, smart building systems, adaptive controls, and digital infrastructure. The framework is an enabling route for predictive management, efficiency, economic viability, and sustainability. Source: Authors' workstation.

Smart Building Ecosystems are comprised of Internet of Things (IoT)-enabled sensors, smart meters, intelligent HVAC systems, automated lighting, and controls that respond to occupancy needs (Mukilan et al., 2024). These networks monitor how energy is used, temperature, real-time data on occupancy levels, humidity, and air quality.

This way, building performance is optimised while predictive control is enabled. Building performance is also observable through the enablement of user recognition patterns and adaptive judgments, as made possible by machine learning algorithms (MLA) and artificial intelligence (AI) (Fatema et al., 2025). According to Ghaffarianhoseini et al. (2019), smart building systems are complemented by digital infrastructure through the facilitation of remote monitoring, system integration, and data-based operational management. These smart building systems come in the form of building management systems (BMS), cloud-based platforms, digital twins, and data analytics dashboards.

The framework of the 4IR technology is founded on such smart building systems that must offer efficiency optimisation, economic rationality, and lifecycle performance (Khan & Alsabban, 2023). These performance indicators position residential buildings as contributors to sustainable economic development.

The duo of BED and 4IR technologies have definitive impact on building performance towards the improvement of the economic viability of residential architecture (Ding et al., 2024). Their integration is expected to front a synergistic blueprint. The blueprint must define how 4IR technologies define how building performance is tracked, optimised, and sustained, while biophilic design underlines what comprises environmentally-responsive design that is human-centred.

METHODOLOGY

Research Design

Qi et al. (2025) and Yaolin et al. (2025) guided the adoption of a systematic review research design. Such a design is necessary to ensure the integration of BED and 4IR technologies in residential architecture towards synthesising their existing conceptual and empirical evidence.

This research route is considered appropriate because it is aimed at collating and analysing fragmented knowledge, comparing results across multiple contexts, and noting the trajectory of research patterns and lacunae in a transparent, reproducible, and structured manner.

The systematic review was guided by the Preferred Reporting Items for Systematic Reviews and Meta-Analysis (PRISMA) framework due to its widespread acceptance and rigour of methodology in built environment and sustainability research domains (Olabode et al., 2023; Ibrahim & Seyed, 2024; and Opeyemi et al., 2025).

The PRISMA can minimise bias through screening, explicit search reportage, and selection procedures (Matthew, et al., 2021). To this end, transparency in the identification of literature, eligibility assessment, and synthesis of results related to human-centred, economic, and environmental outcomes of 4IR-BED integration is ensured.

Search Strategy

Four major academic databases provided veritable resources for a comprehensive literature search. They include ScienceDirect, Web of Science, Google Scholar, and Scopus. These resources were selected to guarantee extensive disciplinary coverage that revolves around architecture, the science of sustainability, engineering, and research in smart buildings. As shown in studies conducted by Morano et al. (2021), Raja et al. (2025), Matthew et al. (2017), and Melissa et al. (2021), queries were floated using thematic keywords and Boolean Operators extracted from the study objectives.

Table 1: Boolean Search Structure adopted across Databases

Thematic Cluster	Boolean Search Expression (Title, Abstract, Keywords)
Biophilic Design Terms	("biophilic design" OR "biophilic environmental design" OR "biophilia in architecture")
4IR / Smart Technology Terms	("fourth industrial revolution" OR "industry 4.0" OR "smart building*" OR "smart residential building*" OR "internet of things" OR "IoT" OR "artificial intelligence" OR "AI" OR "machine learning" OR "ML" OR "building management system*" OR "BMS" OR "digital twin*" OR "data-driven building*")
Residential Context Terms	("residential building*" OR "housing" OR "residential architecture" OR "smart home*" OR "domestic building*")
Performance & Sustainability Outcomes	("energy efficiency" OR "indoor environmental quality" OR "IEQ" OR "thermal comfort" OR "visual comfort" OR "wellbeing" OR "occupant satisfaction" OR "operational cost*" OR "lifecycle performance" OR "carbon emission*" OR "sustainable development")
Final Combined Boolean String	(Biophilic Terms) AND (4IR Terms) AND (Residential Terms) AND (Performance Terms)

Notes. Filters applied include 2010 – 2025 publication years, English as the language of publication, and peer-reviewed journals, conference papers, and grey literature.

Title, abstract, and keywords refined searches towards improving relevance. Lists of references from selected papers and articles were screened manually to identify additional studies considered relevant and important.

Criteria for Inclusion and Exclusion

Table 2 shows the precise criteria for inclusion and exclusion used in the selection of papers for the PRISMA framework. This is to ensure consistency and relevance.

Table 2. Inclusion and Exclusion Criteria for the Selection of Studies

Category of Criteria	Criteria for Inclusion	Criteria for Exclusion
Period of publication	Papers published between 2010 and 2025	Studies conducted before 2010
Type of document	Journal articles, relevant gay literature, and conference papers that are peer-reviewed	Commentaries, editorials, and pieces of opinion with empirical and grounded conceptual and theoretical foundation
Language of communication	Papers delivered in the English Language	All non-English publications
Type of Building	All studies directed at housing and residential architecture	Studies focused squarely on non-residential building typologies, including public and industrial typologies
Thematic priority	Studies that address BED, 4IR technologies, and/or their integration	Studies that are not related to BED, intelligent and digital building technologies
Results	Studies that report on economic, operational, environmental, and human-focused outcomes. Such outcomes must revolve around cost performance, wellness of occupants, IEQ, and energy efficiency.	Research engagements that lack clear outcome approaches and indicators of performance
Rigour of methodology	Research engagements with clear-cut research design, sources of data acquisition, and methods of analysis	Studies with abstract and undocumented methodologies

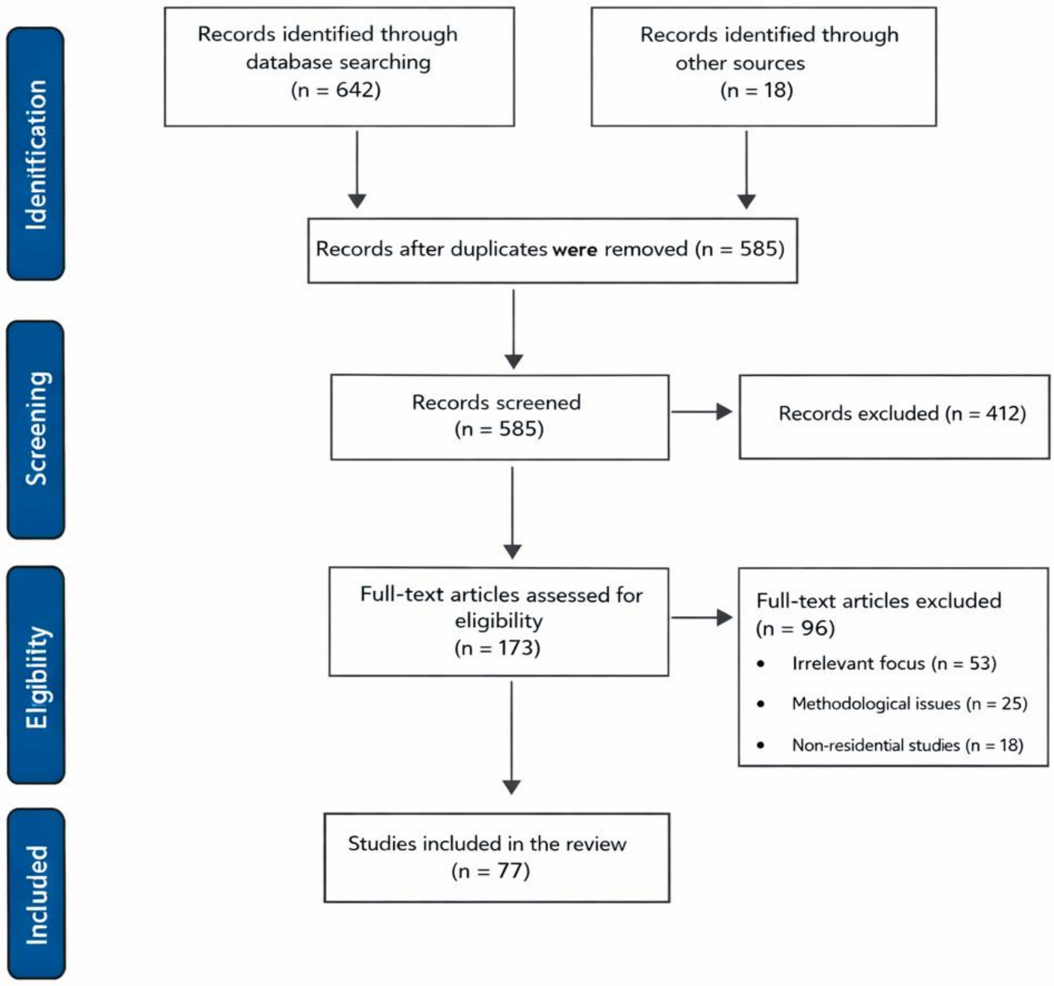
Relevance to narratives in sustainability	Studies that contribute to economic performance in housing and sustainable development	Studies that are devoid of relevance to development and KPIs in sustainability

Notes. Table 2 defines the criteria used to methodically include relevant studies and exclude non-relevant literature. This ensures methodological rigour, consistency with review objectives, and thematic relevance.

Process of Study Selection

The process of study selection followed the PRISMA four-stage route that includes identification, screening, eligibility, and inclusion. Foremost database searches provided a generic count of records, which were first screened for duplicates. Titles and abstracts were subjected to a review process to remove irrelevant research materials. Full-text papers of relevant and eligible studies were examined with the criteria of inclusion. Results of the final selection constituted the dataset for synthesis.

Figure 3. The PRISMA Flow Diagram



Notes. The PRISMA flow diagram informed the selection of the 77 peer-reviewed studies. The list is available as supplementary materials. Source: Authors' workstation.

Figure 3 captures the PRISMA flow diagram that was developed to document the number of sourced studies, screened, excluded, and included at the last stage that informed the '77'. This is towards ensuring replicability and transparency of the entire review process.

Extraction of Data and Coding

The Structured Data Extraction Matrix (SDEM) was developed to extract relevant information from the selected seventy-seven (77) studies. Variables that guided the precision of the extraction matrix include: (a). author(s)

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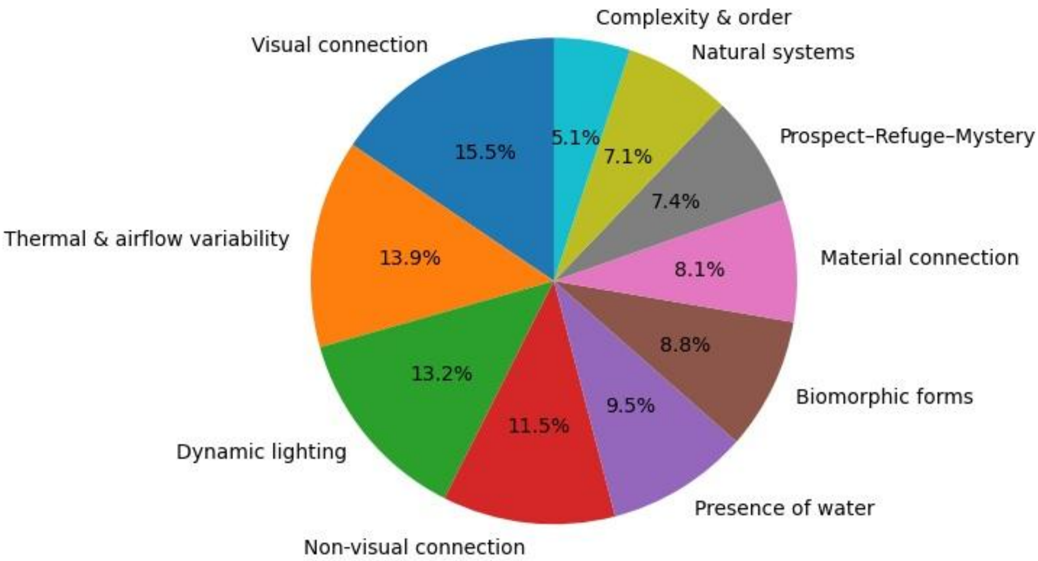
and the year of their publication, (b). study area/geographic context, (c). research design and methods adopted, (d) employed BED strategies, (e) implemented 4IR technologies, (f) environmental outcomes which include emissions, IEQ, and energy efficiency, (g) economic outcomes such as lifecycle performance and cost savings, and (h). human-centred outcomes such as satisfaction, comfort, and wellness.

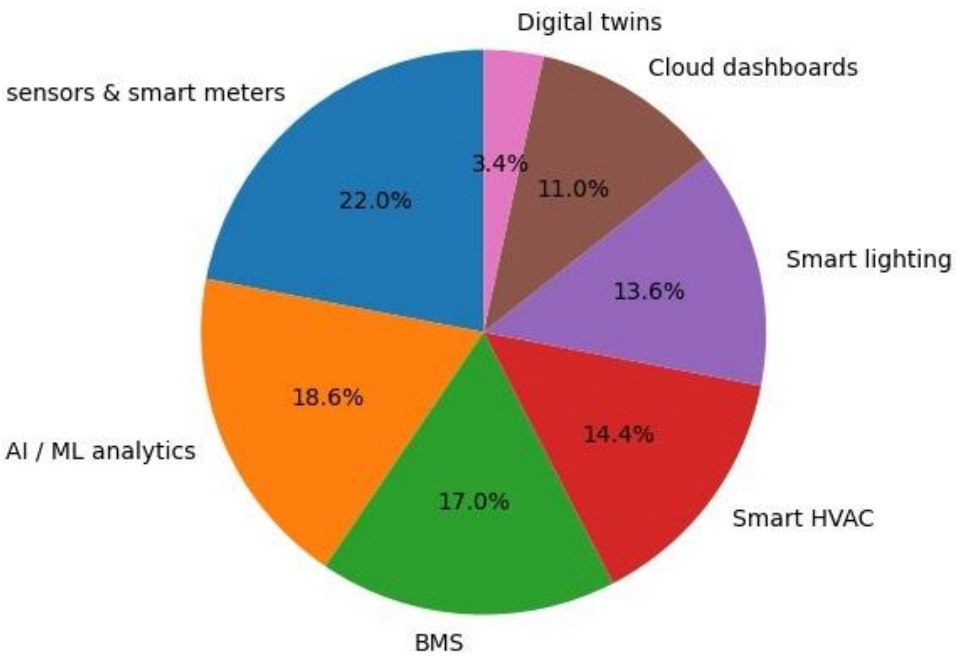
The studies were deductively and inductively coded into six (6) dominant thematic domains, which are in tandem with BED/4IR integration outcomes. These six (6) domains include (a). Strategy themes for BED (b). Themes for 4IR technology (c). Themes for environmental Outcome (d). Economic Outcome themes (e). Themes for human-centred outcome, and (f). Research design distribution. The thematic frequency pie charts (n = 77 studies), Figures 3 to 7, illustrate the performance of sub-themes under each theme across the entire dataset.

Figure 4. Strategy sub-themes for Biophilic Environmental Design (BED)



Notes. ‘Visual connection to nature’ has the highest frequency, while the lowest frequency is from studies that mention ‘complexity and order’. Source: Authors’ workstation.

Figure 5. Sub-themes under Fourth Industrial Revolution (4IR) technology



Notes. ‘IoT sensors and smart meters’ has the highest frequency, while there is significant low frequency of studies that mention ‘digital twins’. Source: Authors’ workstation.

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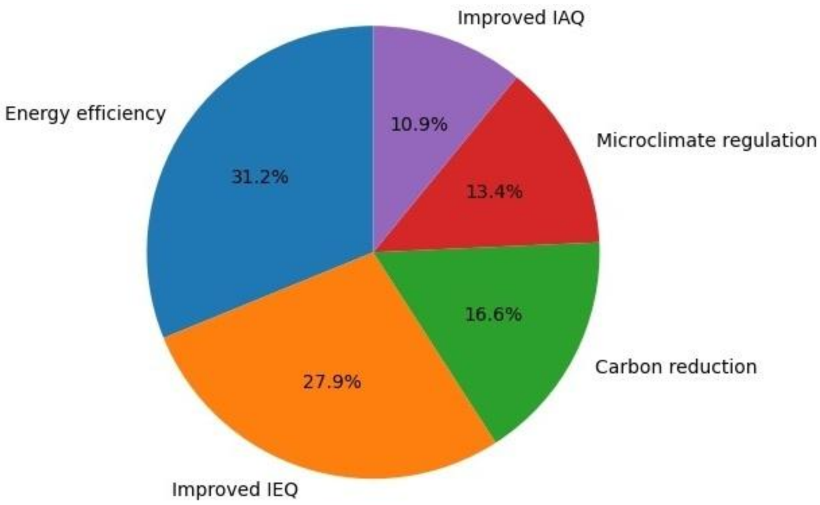
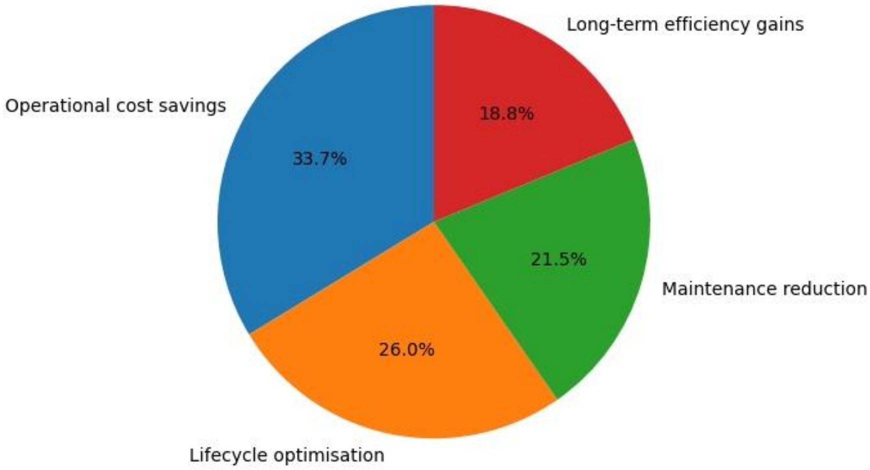
Figure 6. Sub-themes under Environmental Outcomes



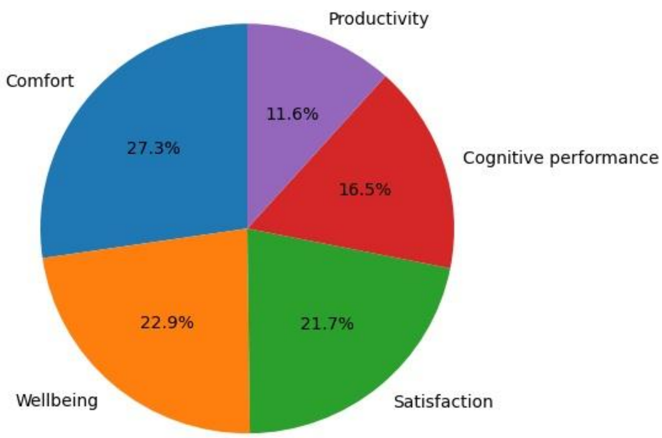
Notes. The highest frequency for themes on environmental outcomes is ‘energy efficiency’, while mentions of ‘improved IAQ’ generated the lowest frequency. Source: Authors’ workstation.

Figure 7. Economic Outcomes Theme and sub-themes



Notes. The highest frequency for themes on economic outcomes is ‘operational cost savings’, while mentions of ‘long-term efficiency gains’ generated the lowest frequency. Source: Authors’ workstation.

Figure 8. Human-centred Outcomes Theme and sub-themes



Notes. ‘Comfort’ has the highest frequency, while the lowest frequency is from studies that mention ‘productivity’. Source: Authors’ workstation.

Data Analysis

A narrative synthesis of the seventy-seven (77) peer-reviewed studies shows that there is a strong convergence of Fourth Industrial Revolution (4IR) technologies and Biophilic Environmental Design strategies towards the advancement of sustainable residential building performance.

A pattern of defined and clear performance is observed across diverse methodologies, from post-occupancy evaluations and simulation-based studies to sensor-powered field measurements.

The Narrative Synthesis and Thematic Integration Matrix in Table 3 defines themes for the BED, 4IR technologies, results, comparative insights vis-à-vis, integrated and independent (standalone) findings.

The comparative and thematic analysis in Table 4 enables the identification of performance trends, patterns that recur, and relationships between 4IR technologies and BED approaches.

The analysis guides evidence-based integration by focusing on sensor-driven and adaptive biophilic approaches. This synergy.

Which is in tandem with human wellness and energy performance, will inform decisions, selection of technologies, and frameworks that are bespoke and context-specific to emerging economies.

Table 3. The Narrative Synthesis and Thematic Integration Matrix

	Dominant Patterns (as extracted from pie charts)	**BED/4IR Findings (Integrated)**	**BED or 4IR Findings (Standalone)**	**Relationships and Performance Trends**	**Research Gaps and Key Limitations**
Major BED Strategies according to %s	Visual connection to nature. Thermal & airflow variability. Dynamic lighting.	BED approaches become adaptive rather than static when interfaced with IoT sensors, AI-driven HVAC, and smart lighting. This enables real-time optimisation of energy use and comfort.	BED lacks adaptability to changing occupant behaviour and climate when applied as passive design, even though it improves comfort.	Integrated networks show stronger connectivity between thermal/visual biophilia and energy efficiency.	Limited empirical validation of complex biophilic patterns, such as complexity & order in digital environments.
Sensory & Experiential Design	Non-visual sensory connection. Presence of water. Biomorphic forms.	Sensors and AI improve the regulation of acoustics, humidity, and lighting. This helps to amplify multisensory biophilic gains.	Sensory strategies enhance personal satisfaction. However, they are difficult to measure without digital monitoring.	Synergised strategies indicate clearer correlations between metrics of IEQ and sensory biophilia.	Frameworks of measurement for non-visual biophilic effects are still underdeveloped.
Spatial Psychology of 'Nature of the Space) –	There is a moderate level of adoption	AI-driven space-use and lighting analytics support adaptive spatial	Key point in architectural theory.	Integrated constructs facilitate user satisfaction and cognitive performance.	There are very limited longitudinal studies that

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Prospect, Refuge, Mystery.	across studies.	experiences. Such an outcome is in tandem with user behaviour.			connect spatial psychology in architecture to the long-term well-being of occupants and smart systems.
Dominant 4IR Technologies	IoT sensors. AI/Machine Language Analytics. Building Management System (BMS).	Continuous feedback loops are enabled. This helps to quantify biophilic intent.	Standalone smart systems focus more on occupant experience, downplaying efficiency.	There are high levels of strong synergy observed between biophilic comfort strategies and AI-driven controls.	Digital twins are underutilised. This is mainly an issue of cost and a dearth of concomitant skills.
Environmental Performance	Energy efficiency. Improved IEQ.	Integrated BED–4IR strategies consistently present higher savings in energy and better regulation of the microclimate.	Independent strategies show fragmented performance.	Synergised approaches indicate more benefits across IEQ, energy savings, and reduction of emissions.	There is a constrained carbon lifecycle assessment that connects biophilic implementation with digital control.
Human-Centred Outcomes	Comfort. Wellbeing. Satisfaction. Cognitive performance.	Synergised constructs exhibit stronger and consistent improvements across all human-centred metrics.	Improvements offered by standalone approaches are linear.	There is an adaptive biophilic environment/occupant wellbeing relationship.	There is weak evidence of productivity outcomes in residential contexts.
Economic Outcomes	Cost savings. Lifecycle performance.	Energy optimisation and predictive maintenance improve the efficiency of the building's lifecycle.	There is evident savings in initial cost. However, long-term economic benefits are vague.	Integrated systems outperform independent constructs in the reduction of operational cost.	There is a dearth of studies that address affordability in low-income housing.
Sustainable Economic Development Implications	Increasing confluence of 4IR and BED.	Integrated approaches facilitate productivity, health, and operational efficiency. These remain the key drivers of sustainable economic value.	Independent approaches are limited in the promotion of a systemic economic impact.	Integration processes are harbingers of holistic value creation.	There is a need for a bespoke, place-based, and context-sensitive framework for developing and emerging economies.

Notes. The matrix contextualises and interprets evidence towards explaining causal relationships, meanings, and mechanisms across multiple studies.

This supports theoretical consolidation, conceptual clarity, and the development of an evidence-informed integration framework that is holistic for residential architecture. Source: Authors' data analysis manuscripts.

Table 4. BED-4IR Integration in Residential Architecture: A Comparative and Thematic Analysis

Thematic Dimension	Most occurring BED Strategies	Supporting 4IR Technologies	Recurring Performance Trends	Key Human-Centred Outcomes	Interpretive Insight
Sensory & Perceptual Connection	Visual connection to nature (59.7%). Thermal and Airflow Variability (53.2%). Dynamic lighting (50.6%).	IoT sensors & smart meters (75.3%). Artificial Intelligence/Machine Language analytics (63.6%). BMS systems (58.4%).	Energy efficiency gain (31.2%). Improved IEQ (27.9%).	Thermal/visual comfort (88.3%); Occupant wellbeing (74%)	Digital control enhances sensory biophilia by enabling adaptive lighting and visual comfort optimisation
Environmental Adaptability	Thermal & airflow variability (53.2%). Presence of water (36.4%).	Smart HVAC systems (49.4%). BMS (58.4%).	Energy efficiency (31.2%). Microclimate regulation (13.4%).	Occupant wellbeing (74.0%). Visual comfort (88.3%).	Real-time sensing and automation transform static biophilic elements into responsive environmental systems.
Spatial Experience & Psychological Restoration	Prospect–Refuge–Mystery (28.6%). Biomorphic forms & patterns (33.8%).	AI/ML analytics (63.6%). Cloud dashboards (37.7%).	Moderate gains in IEQ. Limited reportage on carbon reduction.	Cognitive performance (53.2%). Wellbeing (74.0%).	Psychological benefits are enhanced when spatial biophilia is supported by adaptive monitoring. This is often under-quantified.
Materiality & Nature Integration	Material connection with nature (31.2%). Natural systems integration (27.3%).	BMS (58.4%). Digital twin (11.7%).	Energy efficiency (31.2%).	User satisfaction (70.1%). Comfort (88.3%).	Material biophilia benefits are strongest when monitored digitally. However, systems-level integration remains weak.
Complexity & Ecological Order	Complexity & order (19.5%).	Digital twins (11.7%).	Inconsistent economic and environmental outcomes.	Cognitive performance (53.2%). Wellbeing (74%).	Low adoption indicates a research gap in modelling ecological complexity using advanced digital tools.
Integrated BED–4IR Systems	A combination of visual connection, thermal variability, and dynamic lighting.	IoT plus AI plus BMS.	Strongest performance across energy savings, emissions	Comfort (88.3%). Wellbeing (74.0%). Satisfaction (70.1%).	Integrated approaches outdo independent constructs of BED and 4IR technologies. This

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			reduction, and IEQ.		enables adaptive and predictive building behaviour.
Standalone Implementations	A single biophilic feature or an isolated smart technology.	Basic IoT controls	Localised gains. Limited long-term efficiency.	Short-term improvement in comfort.	Lack of systemic integration reduces economic viability and scalability.

Notes. The comparative and thematic analysis contrasts and evaluates, identifying recurring patterns, weaknesses, and strengths between standalone and integrated BED/4IR applications. Source: Authors' data analysis manuscripts.

Quantitative Summary and Cross-comparative Synthesis

Table 4 presents statistics of % reporting energy savings, and improvements in IEQ that are directly compared to standalone BED, standalone 4IR, and integrated BED/4IR outcomes using a summary comparison table. The table also shows the magnitude of differences, recurring effect patterns, and contradictions.

Table 5: Summary Comparison Table: Standalone BED/4IR Performance vs Integrated (n = 77 studies)

Performance Dimension	Standalone BED	Standalone 4IR Technologies	Integrated BED–4IR Systems	Magnitude of Difference	Recurring Patterns	Key Contradictions / Gaps
Energy Efficiency	Passive reductions via daylighting, ventilation, and thermal variability.	Real-time optimisation through IoT (75.3%), AI/ML (63.6%), BMS (58.4%).	Strongest and most consistent energy savings through adaptive optimisation.	Integrated systems show broader and more sustained gains than isolated applications.	Sensor-driven cooling, smart lighting, and predictive control are repeatedly linked to lower energy demand.	Limited full lifecycle carbon assessments despite reported energy gains.
Indoor Environmental Quality (IEQ)	Improved visual & thermal comfort; often perception-based.	Continuous monitoring of temperature, humidity, and IAQ.	Measurable plus adaptive IEQ enhancement. Stronger microclimate regulation.	Clear amplification effect when digital monitoring supports biophilic intent.	Adaptive lighting and airflow variability repeatedly enhance IEQ metrics.	Improved IAQ is the least-reported environmental outcome (27.9%).
Human-Centred Outcomes	Comfort and wellbeing frequently reported.	User-responsive controls improve satisfaction.	Highest performance: Comfort (88.3%), Wellbeing (74%), Satisfaction (70.1%).	Integrated models demonstrate the strongest magnitude of human-centred benefits.	Recurring link between adaptive environments and stress reduction.	Productivity is weakly evidenced in residential contexts.
Economic Performance	Initial cost benefits; indirect health value.	Operational cost savings through predictive maintenance.	Reduced operational costs plus improved	Integrated systems outperform in long-term	Predictive maintenance is consistently	Affordability challenges in low-income housing; vague

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			lifecycle efficiency.	operational savings.	linked to cost reduction.	long-term ROI data.
Environmental Sustainability	Microclimate regulation. Reduced mechanical reliance.	Energy/emissions monitoring.	Stronger emissions reduction trends when combined.	Integration yields systemic sustainability rather than fragmented gains.	Real-time optimisation transforms passive design into responsive systems.	Limited digital twin usage (11.7%); low modelling of ecological complexity.
System Adaptability	Static once implemented.	Adaptive but sometimes detached from design intent.	Predictive, responsive, ecosystem-based performance.	Highest adaptability observed in integrated models.	Feedback loops repeatedly improve comfort-energy balance.	Interoperability and regulatory gaps constrain scaling.

Notes. Integrated systems perform better than standalone BED and 4IR in energy, comfort, wellbeing, and lifecycle savings. However, carbon lifecycle evidence and affordability remain constrained. Source: Authors' data analysis manuscripts.

Table 6: Comparison of Quantitative Performance: Integrated BED/4IR Systems (n=77)

Performance Indicator	Average Improvement (%) Across Integrated Systems	Reported Range (%)	Comparison with Standalone Applications	Recurring Quantitative Pattern
Energy Savings	27%	15–35%	8–18% (Standalone BED); 12–22% (Standalone 4IR)	Passive biophilic strategies amplified by AI-driven optimisation and smart HVAC
Indoor Environmental Quality (IEQ) Improvement	24%	10–32%	8–15% (Standalone BED); 12–20% (Standalone 4IR)	Strongest gains observed in thermal and visual comfort when sensor-driven adaptive lighting and airflow variability were applied.
Operational Cost Reduction	21%	12–30%	5–12% (Standalone BED); 10–18% (Standalone 4IR)	Predictive maintenance and energy optimisation are repeatedly linked to lifecycle cost savings.
Carbon Emission Reduction	18%	8–25%	5–15% (Standalone approaches)	Emission reduction is more consistent when passive cooling is digitally optimised.
Occupant Comfort & Wellbeing (Reported Frequency Proxy)	74–88% reporting improvement	—	Lower magnitude and less consistency in standalone models	Adaptive feedback loops consistently strengthened comfort-energy balance

Notes. Integrated Bed/4IR systems show better energy, cost, IEQ, and comfort performance as compared to standalone biophilic and smart applications. Source: Authors' data analysis manuscripts.

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RESULTS

Overview of Studies Selected for the Review

The reviewed seventy-seven (77) studies presented a geographically varied research terrain. Forty-two (42) studies originating from Africa and South America reflected a budding interest in context-responsive and sustainable residential design. Most of the studies showed strong representation from Ghana, South Africa, Nigeria, Brazil, Peru, Colombia, and Argentina. Asia and the Middle East region contributed thirty-one (31) studies that highlighted the advanced adoption of biophilic strategies and smart residential technologies. Studies from this region came from India, South Korea, Singapore, Japan, the UAE, and China. The North American region presented only three (3) studies, all from Mexico. This indicates a research gap in residential-focused BED/4IR integration obtainable within the South American context. Only one (1) study came from the European enclave. This is suggestive of an under-exploration of an integrated biophilic-digital residential network, despite the fact that the discourse of sustainability in the region is appreciably strong. It must be stated here that the majority of reviewed studies (≈98-7%) originate outside North America and Europe. This indicates that most empirical evidence is extracted from Global South contexts. The dataset of reviewed studies indicated a blend of post-occupancy evaluations, simulation-based studies, surveys, sensor-driven field measurements, and conceptual frameworks.

Table 7: Research Method Distribution across reviewed studies (n= 77)

Research Method Category	Number of Studies (n)	Percentage (%)	Typical Application in Reviewed Studies
Simulation & Modelling Studies	24	31.2%	Energy modelling, smart system optimisation, predictive cooling, and lighting analysis
Post-Occupancy Evaluation (POE)	18	23.4%	Assessment of comfort, well-being, and user satisfaction
Sensor-Based Field Measurements (IoT Monitoring)	15	19.5%	Real-time IEQ tracking, energy use monitoring, adaptive control validation
Survey-Based / Questionnaire Studies	10	13.0%	Perception studies on biophilic experience and smart housing adoption
Conceptual / Framework Development Studies	7	9.1%	Theoretical integration models of BED and 4IR
Mixed-Method Studies (Simulation + Field + Survey)	3	3.8%	Combined environmental and human-centred performance validation
Total	**77**	**100%**	—

Notes. The distribution indicates a dominance of simulation-driven research, while experimentally and longitudinally validated integration investigations remain underrepresented. Source: Authors' data analysis manuscripts.

Simulation and modelling sessions featured extensively in studies that had extensive narratives on smart systems and efficiency. Surveys and post-occupancy assessments were deployed in human-centred investigations, while a dearth of longitudinal and experimental studies remained significant.

Outcomes on Environmental Performance

There are reported improvements in visual and thermal comfort, IEQ, and effective ventilation for residential buildings with integrated BED/4IR. Sensor-enabled tracking and adaptive controls strengthened the performance of biophilic strategies. This translates design intent into indoor environmental benefits that are measurable.

Energy efficiency emerges as the notable environmental outcome that is often reported. Investigations show that independent constructs are surpassed by synergised systems. This is measurable in predictive cooling control, real-time optimisation, and adaptive lighting, leading to reduced carbon emissions and energy demand. However, there are still limited full lifecycle assessments.

Human-centred Outcomes

Gains on human-centred metrics are significantly evident. ‘Comfort’ came in as the most reported outcome. Others are ‘wellbeing’ and ‘satisfaction’. Integrated environments exhibited more versatile and consistent improvements in stress reduction, perceived environmental quality, and psychological restoration when compared to conventional designs.

Outcomes on Economic Outcomes

Savings on operational costs are the dominant economic outcome. This is majorly driven by predictive maintenance, energy optimisation, and reduced system inefficiencies supported by 4IR technologies.

Comparative Performance Analysis

Conventional residential designs are consistently outperformed by integrated biophilic/4IR residential schemes. This is evident across human-centred, environmental, and economic indicators. Unlike conventional living units, where performance benefits are detached and fragmented, integrated systems support predictive, adaptive, and user-responsive environments. Such synergy presents higher energy efficiency, superior IEQ, reduced costs of operation, and improved occupant wellbeing. Results underscore integration as a critical route towards human-centred, economically viable, and sustainable residential architecture.

Comparative Insights (Magnitude, Patterns, and Contradictions)

Integrated BED/4IR systems show the greatest magnitude of human-centred impact, as shown in comfort (88.3%) and wellbeing (74%).

This surpasses standalone applications that indicate linear and isolated improvements. Energy performance shows a recurring amplification pattern where passive biophilic strategies become more effective when digitally optimised through IoT, thus making for a more sustained reduction in energy demand.

Standalone 4IR technologies achieve operational efficiency. However, they contradict experiential objectives as smart optimisation without biophilic intent may overlook sensory quality and psychological restoration. Standalone BED enhances perceived environmental quality but lacks adaptive measurability.

Economic benefits are clearer in integrated systems. This is the case where predictive maintenance and energy optimisation repeatedly correlate with operational cost savings. Contradictions, though, persist in long-term lifecycle validation and affordability modelling.

A systemic contradiction exists in digital twin underutilisation and the carbon lifecycle. This is even when there are strong claims of environmental sustainability and adaptive performance.

DISCUSSION

Synthesis of Findings

There is a strong mutual relationship between Fourth Industrial Revolution (4IR) technologies and Biophilic Environmental Design (BED) in residential architecture.

Figure 9: The Integrated Conceptual Framework Linking Biophilic Environmental Design, 4IR Technologies, and Sustainable Development Outcomes in Residential Architecture.

Notes. An integrated conceptual framework showing how BED strategies, enhanced by 4IR technologies, facilitate environmental, human-centered, and economic gains, thus supporting sustainable residential development. Source: Authors' workstation.

BED defines 'what' comprises ecologically responsive design. 4IR technologies underscore 'how' such intentions are tracked, enhanced, and sustained. The synthesis of the two paradigms demonstrates that integration presents quantifiable environmental benefits, clearer economic gains, and stronger human-centred outcomes when compared to when they are independent applications. To this end, 4IR technologies and BED operate not as parallel systems but as mutually reinforcing constructs. Such symbiosis improves the capacity for resilience, predictive control, and observational quality in housing.

Significance for Sustainable Residential Architecture

Outcomes offer further discourse in residential architecture from a paradigm of passive shelter to an intelligent and responsive ecosystem. Architects in Global South contexts should integrate digital infrastructure alongside biophilic approaches at early stages of design. Such action must consider local climatic, economic, and socio-cultural conditions, rather than implementing smart technologies as an afterthought. Optimisation of performance outweighs episodic occurrences as buildings can adjust lighting, airflow, and temperature in real time through AI and IoT-enabled feedback loops. This way, energy efficiency and IEQ are assured. Such integration improves occupants' sensory comfort, psychological restoration, and perceived environmental quality.

Adaptive biophilic environments reinforce occupant satisfaction and engagement, thus lending support to the discourse that housing sustainability must prioritise optimising energy metrics as well as experiential performance.

Significance for Sustainable Economic Development

The review concretises a fact which affirms that integrated BED/4IR housing is a factor that escalates sustainable economic development. Reductions in operational cost, made possible through energy optimisation and predictive maintenance, improve lifecycle performance. Indirect viable benefits manifest from reduced stress, improved health, and enhanced occupants' cognitive performance. In addition, adaptive systems improve resilience by responding to fluctuating demands in energy and climate variability. Such responsiveness enhances the economic stability of residential investments and reduces long-term risks. To this end, integration of the two constructs supports an interwoven network of economic drivers such as cost-efficiency, productivity, and environmental stewardship.

Implementation challenges and success factors

Integrated BED/4IR strategies face high upfront costs, limited digital literacy, and technical skill gaps in low-income contexts. Practical adoption is hindered by complex interfaces and infrastructure deficits. Lifecycle cost analyses indicate that, despite higher initial investment, operational savings from energy optimisation and predictive maintenance can offset costs, with estimated payback periods ranging from 5-12 years. This is towards enhancing the feasibility of low-income housing when subsidies are applied. Feasible solutions include simplified smart systems, staged implementation, user training, and local capacity-building. This ensures that residents can effectively engage with adaptive technologies devoid of prohibitive costs or operational challenges.

Research Gaps

A major research gap that exists in emerging economies is the limited validation of place-based empirical research. This is a major concern in study areas where climate, economic conditions, and socio-cultural dimensions differ significantly from global North contexts. Africa and parts of Asia show increasing contributions. However, studies in such climes remain unevenly distributed. Europe and North America also exhibit minimal longitudinal evidence in residential-specific integration. At the end of the day, context-sensitive blueprints that tackle informal housing and climatic extremes are underdeveloped.

Secondly, post-occupancy and long-term economic performance data remain scarce. Most investigations depend on cross-sectional surveys, short-term simulations, and pilot sensor deployments. Overall, there is insufficient longitudinal tracking of maintenance efficiency, lifecycle costs, carbon lifecycle impacts, and user adaptation patterns over long occupancy periods. Without such data, claims of enhanced productivity, sustained wellbeing and economic resilience will remain partially inferential.

Frameworks adopted to measure non-visual biophilic gains lack standardised digital metrics. This limits a robust integration with smart analytics platforms. Instances also abound where studies, including Anderson (2015), Arku (2010), Olabode et al. (2023), Zainab & Doğa (2025), Chinedu et al. (2025), and Das (2025), cited the underexploration of affordability models that reconcile the high cost of smart infrastructures with the realities of low-income housing.

Policy and Practice Implications

Policymakers and developers must prioritise affordable, scalable, and user-friendly implementations of integrated BED/4IR systems. Strategies may include incentivising low-cost sensor packages, offering subsidies for smart-retrofitted housing, and developing simplified interfaces for resident interaction. Regulations should incorporate context-specific performance standards that consider financial and technical limitations in low-income areas. Architects and engineers are encouraged to design for incremental adoption, enabling communities in Global South contexts to gradually integrate digital and biophilic elements without incurring prohibitive costs or requiring extensive technical knowledge.

Futuristic Research Route

Even though seventy-seven (77) studies were reviewed using the PRISMA-guided systematic process, a limitation exists where the investigation presents aggregated frequencies, percentages, and thematic summaries without carrying out indepth individual analysis of the studies. To this end, a more granular analysis of contrasting regional findings, a critical appraisal of methodological robustness, contextual differences, contradictions among specific studies, and the quality of research design would strengthen the analytical rigour. Future investigations should focus on empirical and longitudinal research that follows integrated BED-4IR residential schemes over long periods of time. This will assist in validating carbon performance, lifecycle cost savings, adaptive efficiency, and occupant wellbeing. Mixed-method approaches that combine post-occupancy evaluations, sensor-driven data, and digital twins are important for presenting a robust dataset. Going forward, studies must integrate data-driven design with socio-cultural, local climate, and economic contexts, especially in emerging economies. This will help develop place-responsive frameworks.

Research should advance policy integration by founding quantifiable benchmarks of performance, regulatory guidelines, and standardised IEQ metrics that align smart-biophilic housing with economic development goals that are sustainable.

CONCLUSION

This systematic review affirms the fact that integrating BED with 4IR technologies notably improves human wellbeing, environmental performance, and economic efficiency in residential architecture. BED underscores ecologically responsive and user-centred design intent. Such intent is optimised, operationalised, and sustained by 4IR technologies through flexible and data-powered systems. The study offers knowledge by coalescing fragmented evidence into a merged integration framework that connects intelligent building ecosystems with sensory biophilia. Ultimately, integrated biophilic-4IR residential schemes portray a ground-breaking route towards resilient, economically viable, and performance-based housing in Global South contexts. This supports sustainable development that is in tandem with local environmental, social, and economic realities.

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