Multidisciplinary Reviews

BIBLIOMETRIC RESEARCH
Published Online: September 18, 2025
https://doi.org/10.31893/multirev.2026189

An ESG based smart buildings assessment framework: A bibliometric and conceptual analysis in the Malaysian context

Mohd Hairwan Md Nor[a] ✉ | **Mohd Syafiq Syazwan Mustafa**[b] | **Fatimah Mohamed Yusop**[b] | **Sri Sumarwati**[c] | **Nur Ameera Mohd Nizam**[d] | **Maranatha Wijayaningtyas**[e]

[a]Department of Skills and Professional, Faculty of Technical and Vocational Education, Universiti Tun Hussein Onn Malaysia (UTHM), Batu Pahat, Johor, Malaysia.
[b]Department of Civil Engineering Technology, Faculty of Engineering Technology, Universiti Tun Hussein Onn Malaysia (UTHM), Pagoh Education Hub, Johor, Malaysia.
[c]Faculty of Technical and Vocational Education, Universiti Tun Hussein Onn Malaysia (UTHM), Batu Pahat, Johor, Malaysia.
[d]Edgenta Greentech Sdn Bhd, The Horizon Bangsar South City, Kuala Lumpur, Malaysia.
[e]Civil Engineering Program, National Institute of Technology Malang, Jawa Timur, Indonesia.

Abstract Integrating Environmental, Social and Governance (ESG) principles into "smart building" development represents a critical step toward sustainable urbanization. This study aims to develop a comprehensive ESG-based assessment framework for smart buildings, specifically within the Malaysian context. To identify key themes, research trends and interdisciplinary relationships, the researchers conducted a bibliometric analysis using VOSviewer, focusing on the co-occurrence of keywords related to smart buildings, sustainability and ESG elements. Findings showed that concepts including smart building, sustainability and governance are fundamental to the dialogue, underscoring the advancing importance of smart infrastructure in meeting the Sustainable Development Goals (SDGs). Rather than employing a standard systematic review, this study adopts a bibliometric technique that visually and quantitatively illustrates the research landscape, offering a comprehensive view of scholarly activity over the previous decade. This study systematically developed a conceptual model, drawing on bibliometric findings to integrate ESG elements into "smart building" assessment. The environmental dimension emphasizes resource efficiency and renewable energy use. The social dimension prioritizes occupant well-being, inclusivity and health. While the governance dimension addresses regulatory compliance, transparency and digital ethics. While regulatory compliance, transparency and digital ethics adressed in governance dimension. This framework enhances sustainable building practices towards national agenda for smart city development and offers a fundamental framework for future smart building.

Keywords: environmental sustainability, social well-being, governance, smart technologies, VOSviewer

1. Introduction

The growing emphasis on sustainability has brought transformative impacts to the architecture, engineering and construction sectors by reshaping the way urban environments are conceptualized and delivered. In Malaysia, this transformation is important due to rapid urbanization with estimates indicating close to 85% of the population will reside in urban areas by 2040 (Kanasan & Hassan, 2023). This projected demographic shift exerts increasing pressure on infrastructure, resource consumption and environmental management. As a result, there is a critical need for innovative and sustainable development approaches. In response to these challenges, the Malaysian government introduced the Malaysia Smart City Framework (MSCF) designed to guide the strategic planning and implementation of smart urban development nationwide (Ministry of Housing and Local Government, 2018). The MSCF is not only aligned with national development agendas but also reflects global imperatives such as the United Nations Sustainable Development Goals (SDGs), which emphasize sustainability, resilience and inclusivity (National Digital Department, 2024).

Smart buildings are emerging as critical enablers within the broader smart city ecosystem. Smart buildings serve as integral components of smart cities, utilizing advanced technologies to enhance resource efficiency and improve the quality of urban life (Mayouf et al., 2024). These structures leverage the Internet of Things (IoT), artificial intelligence (AI) and automation technologies to enhance energy efficiency, reduce environmental impacts and improve occupant well-being (Poyyamozhi et al., 2024). Although technological advancement is frequently the primary focus, the content highlights the importance of integrating Environmental, Social and Governance (ESG) principles into smart infrastructure to achieve holistic sustainability (Zhang et al., 2024; Chopra et al., 2024; Aldowaish et al., 2022; Sadiq et al., 2022). In Malaysia, ESG has become a central pillar of the national sustainability agenda, acting as a strategic tool for investors and financial institutions to evaluate long-term

 Received: June 9, 2025 | Accepted: August 7, 2025

corporate resilience and ethical practices. Despite the developments, implementation of ESG principles within the built environment remains significantly oriented on the environmental dimension. In contrast, the social and governance aspects receive comparatively less attention. For example, although smart technologies are capable of optimizing energy usage and mitigating environmental degradation, the potential to enhance occupant health, promote digital equity, encourage community engagement and ensure ethical data governance is often underutilized (Wei et al., 2024; Goel et al., 2024). In parallel, governance-enabling technologies such as digital twins, blockchain and smart contracts provide tools for enhancing transparency, ensuring regulatory compliance and building trust. However, these technologies are not yet widely integrated into Malaysian smart building practices (Akhtar et al., 2025).

Furthermore, while global assessment tools such as the Smart Readiness Indicator (SRI), SmartScore and SPIRE offer benchmarks for evaluating technological sophistication and digital connectivity but the short fall in providing a comprehensive integration of ESG metrics, particularly those about social inclusivity and governance integrity (Martínez et al., 2021; UL Solutions, 2023). In the Malaysian context, the absence of a national regulatory or assessment framework that explicitly incorporates ESG criteria into smart building development further exacerbates this issue. Consequently, existing approaches lack a systematic framework for assessing the impact of smart buildings on overarching ESG objectives. The outcome causes sustainability efforts to be scattered and could undermine the trust and confidence of investors and other stakeholders. Accordingly, current practices lack a structured mechanism for evaluating how smart buildings support broader ESG goals. This result leads to disjointed sustainability initiatives and may weaken investor confidence and stakeholder trust.

A critical examination of existing literature reveals a significant research gap. While prior studies have primarily focused on the technological aspects of smart buildings such as energy performance, automation and system integration (Billanes et al., 2025; Mayouf et al., 2024; Karoon et al., 2025). There is limited empirical research that systematically explores how ESG dimensions especially the social and governance components can be operationalized within smart building development frameworks. This lack of scholarly attention is particularly evident in developing countries like Malaysia, where urban transformation is accelerating but institutional and regulatory structures remain underdeveloped. Furthermore, there is a lack of dedicated evaluation models that comprehensively incorporate ESG and constraining smart buildings' ability to enable sustainable city transformations. Current frameworks often consider technology-focused perspective and frequently overlook the interconnection of environmental outcomes, social fairness and governance readiness.

Malaysia's vision to become a Smart Nation and achieve Net Zero Carbon emissions by 2050, a paradigm shift is necessary. It is crucial to move beyond viewing smart buildings merely as technological assets. Instead, multi-dimensional socio-technical systems are capable of supporting comprehensive ESG outcomes. This shift calls for the development of an ESG-based smart building assessment framework that evaluates not only environmental performance but also addresses social well-being, digital ethics, public health and governance mechanisms. Therefore, this study is essential and aims to address the existing conceptual and practical void by proposing an integrated ESG based assessment model designed specifically to the Malaysian context. A framework could serve as a blueprint for sustainable urban development, support evidence-based policymaking, attract responsible investments and make a meaningful contribution to both national strategic objectives and global sustainability commitments.

2. Methodology

This study utilizes bibliometric analysis through VOSviewer which is a powerful tool that enables visualization and examination of complex relationships among keywords, authors, citations and institutions in scholarly literature. The generated network maps illustrate the co-occurrence and clustering of keywords across research articles focusing on smart cities, smart buildings, sustainability and Environmental, Social and Governance (ESG) principles. By analyzing node size, proximity and link strength, VOSviewer reveals underlying research trends, core themes and interdisciplinary connections, offering a comprehensive landscape of the academic dialogue (Van Eck & Waltman, 2010; Chen et al., 2021). Unlike systematic reviews, which qualitatively synthesize selected studies based on strict inclusion criteria to provide detailed content and methodological insights (Page et al., 2014). A bibliometric analysis offers a macro-level perspective that highlights evolving focal points and collaborative networks across a broader research corpus (Zupic & Čater, 2015). This approach is particularly valuable in rapidly advancing fields like smart building research, where understanding thematic clusters such as those centered around "smart building" can illuminate key performance indicators and assessment frameworks critical for integrating ESG principles (Nguyen et al., 2022; Shah et al., 2023). The visualization thus underscores the important role of smart building concepts in bridging technological innovation with sustainability and governance metrics. This help to map future directions and identify research gaps in this dynamic field.

2.1. Data collection

Initially, thematic areas were identified to guide the research focus. Data related to smart buildings and smart cities were extracted from the Scopus database. The thematic focus includes smart buildings in relation to environmental, social and governance aspects. Smart cities were incorporated in the search due to the limited availability of research explicitly integrating smart buildings with ESG elements. As outlined in the introduction, smart buildings are integral components of smart cities and several key elements in smart city assessments are applicable to smart building performance evaluations. The Scopus database was selected for its comprehensive coverage and relevance. Figure 1 illustrates the research activities, divided into three stages which are research goal setting, data collection and data analysis.

This study organizes its research process into three structured phases which are setting research objectives, collecting data and conducting analysis, as outlined in Figure 1. Researchers deliberately design each phase to thoroughly and methodically investigate how to integrate Environmental, Social and Governance (ESG) principles into smart building assessments within the Malaysian context. In the first phase, researchers clearly articulated the research goals to establish a strong conceptual foundation. Four primary objectives guided the study which (1) to emphasize the significance of embedding ESG principles in smart building assessment frameworks, (2) to explore existing literature linking smart buildings with ESG elements, (3) to identify specific assessment criteria relevant to ESG dimensions and (4) to develop a conceptual framework that aligns ESG considerations with smart building performance metrics. These goals demonstrate the study’s commitment to addressing both theoretical and practical gaps in current sustainability frameworks.

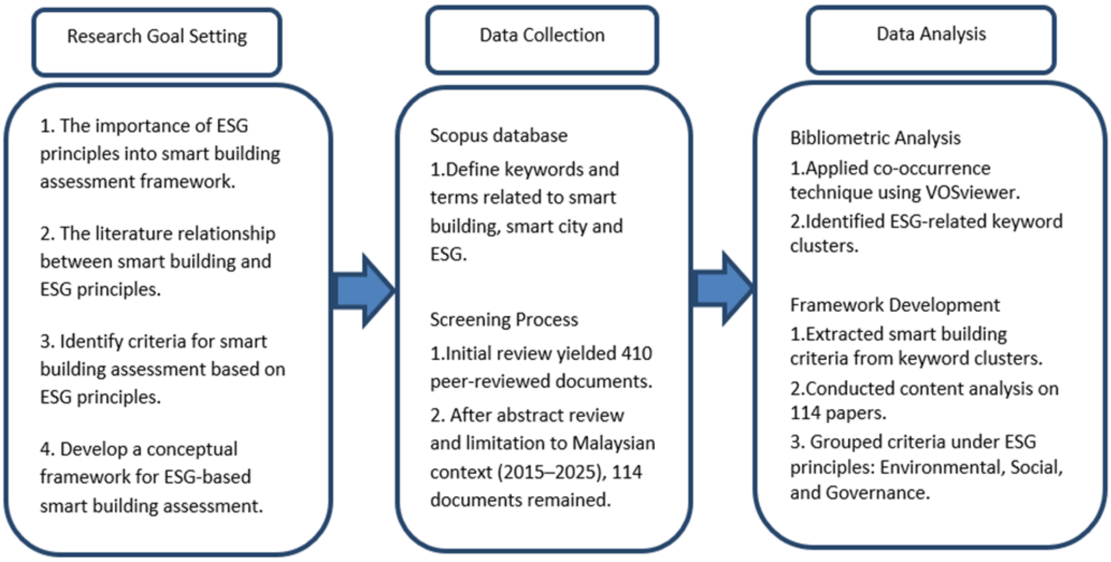

Figure 1 Research activities.

The second phase is data collection, relied on the Scopus database due to its extensive repository of peer-reviewed academic literature and compatibility with bibliometric tools such as VOSviewer. The researchers deliberately and inclusively selected keywords to comprehensively retrieve significant literature such as smart building, smart city and ESG-related terms like environment, social and governance . Using this approach, it systematically gathered key studies for the analysis. This approach ensured a comprehensive retrieval of pertinent literature. An initial screening identified 410 documents. After refining the dataset through abstract reviews and limiting the scope to studies conducted in or related to Malaysia between 2015 and 2025, the researchers reduced the dataset to 114 highly relevant publications. In the final phase, the data analysis involved bibliometric mapping using VOSviewer to perform a co-occurrence analysis of keywords. This technique uncovered thematic clusters and relationships among ESG-related concepts within the smart building discourse. Notably, the analysis enabled the identification of key criteria associated with the environmental, social and governance dimensions. Next, researchers conducted a content analysis of the 114 selected papers to extract, categorize and synthesize these criteria. Organize the findings into a structured framework that groups smart building indicators according to the three ESG principles and providing a comprehensive lens to evaluate sustainability performance.

This sequence steps methodology highlights the study’s rigor and strengthens its contribution to the expanding field of smart and sustainable development. By integrating quantitative bibliometric methods with qualitative content analysis, the research blends data-driven insights with conceptual depth, paving the way for a practical and scalable ESG-based smart building assessment model designed to meet national development goals.

The literature search for this study employed the Scopus database, chosen for its extensive repository of peer-reviewed scholarly publications and its robust bibliometric features. Scopus database for bibliometric studies utilizing tools such as VOSviewer, as it provides well-organized metadata and comprehensive citation indexing, which are critical for visualizing academic trends and research linkages. Researchers constructed the search query to capture relevant studies that explore the intersection of smart technologies and Environmental, Social and Governance (ESG) principles within the Malaysian context. Keywords included such as smart home, smart building, smart city and intelligent building. Along with the variations to ensure broad coverage of documents related to smart and intelligent systems. These terms highlight the study's technological focus, particularly innovations in building design and urban infrastructure.

Researchers designed the search strategy as per Table 1 is to align with the ESG framework by including additional keywords such as environment, environmental, social and governance. These terms targeted studies that directly address enviromental sustainability, social impact and governance, the key pillars of the ESG paradigm. Researchers also included the keyword Malaysia in the TITLE-ABS-KEY field to ensure the search results focused on studies relevant to the Malaysian context. This targeted approach enables the findings to support national policy formulation, inform urban planning and enhance the development of smart infrastructure throughout Malaysia. The use of Boolean operators (e.g., OR, AND) and the structured field search (TITLE-ABS-KEY) helped to refine the search results by ensuring that the retrieved documents were not only topically relevant but also located within the appropriate textual fields, such as titles, abstracts, or keywords. This approach increases the specificity and relevance of the data collected for analysis. Overall, this targeted search strategy ensures that the bibliometric analysis is grounded in high-quality, contextually relevant literature that reflects the integration of "smart" building and city concepts with ESG principles in Malaysia. The results of this search formed the foundation for subsequent bibliometric mapping and thematic clustering using VOSviewer, which enabled the identification of research trends, dominant keywords and potential gaps in the literature.

Table 1 Search strategy.

Database	Search string
Scopus	(TITLE-ABS-KEY ("smart home" OR "smart building" OR "smart city" OR "smart cities" OR "intelligent building" OR "intelligence building" OR "intelligent city" OR "intelligent cities" OR "intelligent building" OR "intelligence building" OR "intelligence city" OR "intelligence cities") AND TITLE-ABS-KEY ("environment" OR "environmental" OR "social" OR "governance") AND TITLE-ABS-KEY (malaysia))

3. Result and Discussion

The integration of advanced technologies in the construction industry particularly in the operation of smart buildings has emerged as a strategic response to complex challenges, interlinked challenges related to energy efficiency, environmental sustainability, social equality and transparent governance (Castro-Lacouture, 2023; Rane, 2023). Beyond the technological adoption, smart buildings represent a paradigm shift in how built environments are conceptualized, designed and managed to serve as foundational elements in the broader evolution of smart cities. These buildings are no longer passive structures instead, it operates as intelligent, responsive ecosystems that optimize resource utilization, personalize occupant experiences and ensure dynamic compliance with evolving global standards and regulatory frameworks. The Internet of Things (IoT), artificial intelligence (AI) and machine learning (ML) have catalyzed the emergence of highly adaptive, occupant-centric building management systems (Sinha, 2024). These innovations enable predictive maintenance, real-time energy analytics and behavioral modeling, fundamentally redefining how buildings interact with both internal and external environments. Importantly, smart buildings are now being assessed not solely through traditional performance metrics but via a multidimensional perspective that includes energy performance, environmental impact, social inclusivity and governance accountability as the dimensions increasingly aligned with Environmental, Social and Governance (ESG) principles.

This evolution requires a more comprehensive and structured evaluation framework that extends beyond technological effectiveness. Key indicators within this framework include renewable energy integration, adaptive thermal comfort systems that respond to user preferences and climate variations, biophilic design elements that foster psychological well-being and robust policy alignment mechanisms. Instead of considering these criteria separately, the framework highlights the interdependencies, recognizing that sustainable performance arises from systemic synergy. In presenting this framework, the paper challenges conventional models of building assessment and proposes an innovative assessment. ESG driven approach that positions smart buildings as ethical, resilient and intelligent entities within the urban development. This approach not only advances sustainability agendas but also reimagines the role of buildings in promoting equility, enhancing liveability and supporting long-term governance goals.

3.1. Data analysis

The VOSviewer analysis visualizes the relationships and connections between smart building criteria and ESG principles. Figure 2 illustrates the strength of the connections among smart building criteria based on ESG principles, which forms the basis of the analysis. The environmental principle is strongly linked to the terms energy efficiency and management, renewable energy, carbon reduction and water and waste management. Smart buildings play an important role in optimizing energy consumption and promoting environmental sustainability.

The social principle within the ESG framework is closely linked to human comfort, passive design strategies, occupant health, well-being, safety and accessibility to essential facilities (Kuok Ho, 2023). The analysis identifies several key areas, including healthcare accessibility and its social implications, the application of advanced technologies such as machine learning for crime prediction and the promotion of inclusivity across diverse backgrounds and abilities. These elements are aligned with social indicators of smart buildings and demonstrate the potential of such developments to improve life quality significantly. Specifically, smart buildings can enhance access to healthcare, reinforce safety measures and support inclusive design through the integration of IoT and AI technologies (Poyyamozhi et al., 2024; Singh, 2025; Alahi et al., 2023). These innovations not only elevate human-centered design but also foster socially responsible communities, directly supporting the social dimension of ESG indicators for smart buildings (Kim & Jeong, 2025).

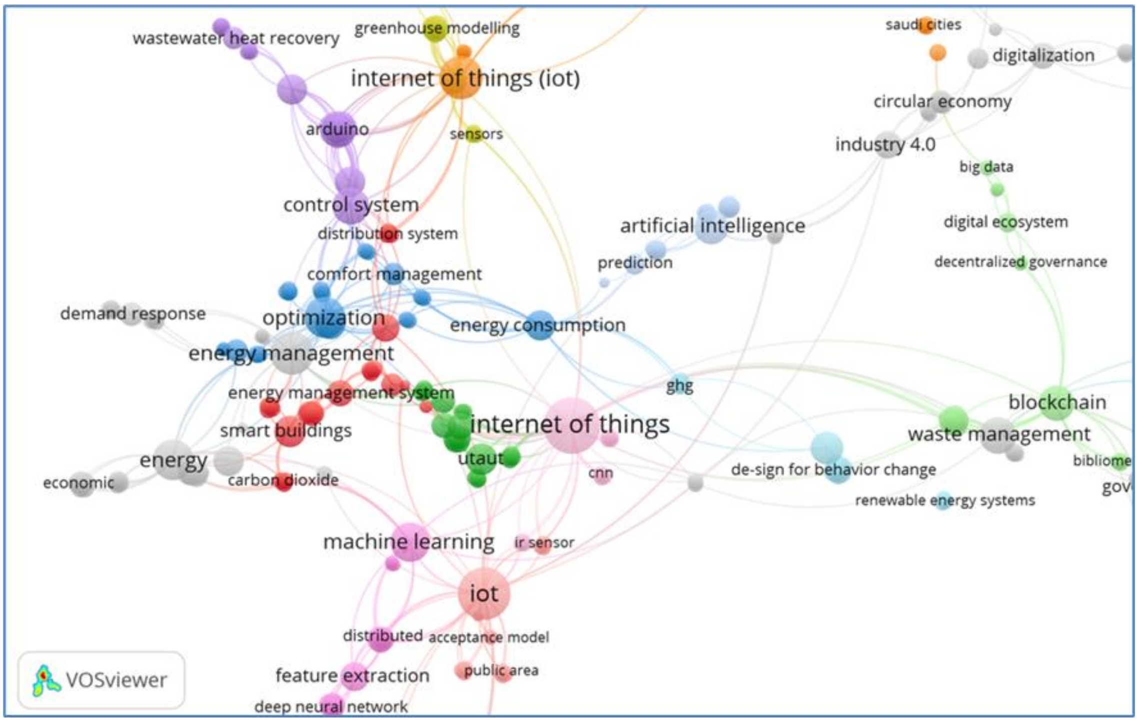

Figure 2 Smart building VOSviewer bibliometric analysis.

The governance principle, on the other hand is increasingly associated with blockchain technologies and decentralized governance models. It underscores the importance of transparency, security and efficiency in the management and operation of smart buildings (Khan et al., 2025; Taboada-Orozco et al., 2024). IoT, AI and machine learning serve as technological enablers that bridge governance with ESG principles by facilitating data-driven decision-making, predictive analytics and sustainable operations. These technologies underpin transparent systems that are integral to smart building frameworks. Furthermore, effective governance frameworks ensure the successful integration of smart technologies, promote citizen engagement and support regulatory compliance as the core elements for smart buildings implementation in urban environments (Kaiser, 2024; Worrakittimalee et al., 2024). Ultimately, governance plays a critical role in advancing sustainability, energy efficiency and environmental stewardship. It provides a strategic foundation for aligning smart building initiatives with the broader objectives of smart cities, ensuring a balanced approach that considers technological advancement, environmental impact and social needs (Chen et al., 2025; Valencia-Arias et al., 2025; Shao & Min, 2025).

3.2. Smart building criteria in environmental element

The environmental element of smart buildings focuses on minimizing ecological footprints through strategies such as enhancing energy efficiency, integrating renewable energy sources, utilizing sustainable materials and conserving resources (Chao, 2013; Mustapha et al., 2025; Orikpete et al., 2023). As illustrated in Figure 3, key environmental criteria that receive significant attention in the literature include the adoption of renewable energy technologies. The application of smart energy meters for real-time monitoring and optimization and the implementation of automated systems for building operation and maintenance. These initiatives are widely supported by ongoing research activities, reflecting the importance in promoting sustainability within the built environment.

Environmental issues have become a global priority in the face of climate change and the depletion of natural resources. Several key areas play a crucial role in addressing these challenges including water conservation, energy efficiency, demand-side energy management, carbon emission reduction and waste management. Each of these components contributes to a more sustainable and balanced ecosystem and should be approached collectively to ensure meaningful environmental progress. Water conservation is a critical necessity as global water demand continues to rise while freshwater availability reducing due to pollution, overuse and climate-related disruptions (Chen & Lai, 2023; El Moll, 2023). Some effective methods such as rainwater harvesting, low-flow fixtures and responsible agricultural irrigation can significantly reduce water wastage. At the policy level, governments must implement regulations that protect watersheds and promote sustainable water use, particularly in regions with limited water resources. Educating the public on the value of water as a finite resource is also crucial to changing consumption habits. Energy efficiency refers to using less energy to perform the same tasks, which helps to reduce greenhouse gas emissions and lower energy costs. It is one of the most cost effective ways to combat climate change. Advanced technology such as LED lighting, energy-efficient appliances and smart building systems are making it easier for households and businesses to reduce energy consumption (Widartha et al., 2024). Moreover, countries that invest in energy efficiency often experience improved energy security, reduced dependence on imports and stronger economic competitiveness. Demand-side energy management (DSM) involves modifying consumer demand for energy through various methods such as incentives, time-based pricing and smart grid technology. Unlike traditional supply-side strategies that focus on producing more energy, DSM emphasizes optimizing energy consumption patterns. This shift is critical in managing peak loads, reducing the strain on power grids and integrating renewable energy sources more effectively (Rehman et al., 2021).

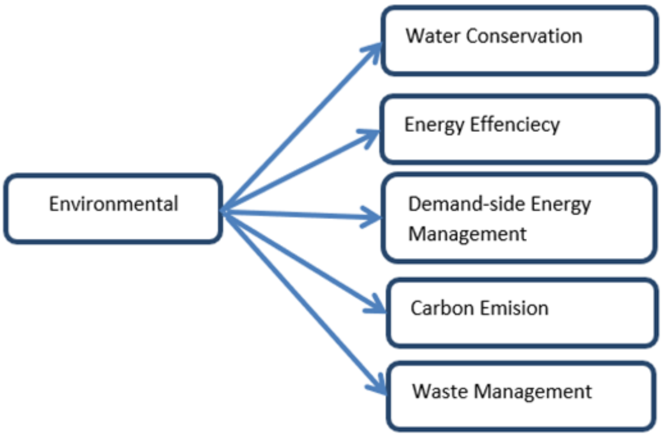

Figure 3 Smart building criteria for environmental element.

Carbon emissions remain the most significant driver of global warming. The burning of fossil fuels in power plants, vehicles and industries releases huge amounts of carbon dioxide into the atmosphere. The emissions can be reduced by combining strategies such as switching to renewable energy sources such as wind and solar to improve public transportation, promoting electric vehicles and deploying carbon capture technologies (Kwilinski et al., 2024). The Paris Agreement highlight the urgency and collective responsibility of nations to curb emissions and limit global temperature rise. Waste management is a fundamental pillar of environmental sustainability. Poorly managed waste contributes to air, water and soil pollution, endangers wildlife and poses serious health risk (Chen & Lai, 2023; FALKNER, 2016). Effective waste management methods includes reducing waste generation, reusing materials, recycling and safe disposal of hazardous substances. The adoption of circular economy principles means designing products for longevity, repairability and recyclability, which can drastically reduce the amount of waste sent to landfills. Community involvement and strict regulatory frameworks are essential in creating cleaner and more sustainable urban environments. A holistic and integrated approach that encompasses water conservation, energy optimization, carbon management and responsible waste handling are required (Vergara-Araya et al., 2020). Authorities, businesses and citizens must work together to create creative solutions and dedicate themselves to lasting changes in behavior. Only through concerted global action can we safeguard the environment and ensure a livable planet for future generations.

The integration of advanced technologies in smart buildings optimizes energy consumption while ensuring occupant comfort and environmental sustainability. Technologies for energy optimization including the Internet of Things (IoT) and Artificial Intelligence (AI), play a critical role by enabling predictive modeling to anticipate energy requirements and proactively regulate system performance. These intelligent systems can result in energy savings of up to 35% across whole-building operations (Lee et al., 2022). Similar findings by Aghili et al. (2025) demonstrated that integrating AI-based controls in heating, ventilation and air conditioning (HVAC) systems can lead up to 40% reduction in energy consumption. Optimization of energy consumption powered by Artificial Intelligence (AI) not only reduces operational expenses but also plays a crucial role in decreasing carbon emissions, thereby supporting national and international climate objectives, such as the Paris Agreement. Moreover, smart buildings are increasingly incorporating renewable energy systems especially on-site photovoltaic (PV) solar panels, to generate clean energy and reduce dependence on conventional power grids. The integration of hybrid systems such as wind turbines, further improves energy resilience and expands the diversity of the energy portfolio. These systems are essential for achieving net-zero carbon goals and promoting energy autonomy (Maka et al., 2024). Wheeler et al. (2022) demonstrated that combining photovoltaic systems with smart inverters enables buildings to actively cut carbon emissions by up to 42% in just one year. However, the intermittent nature of renewable energy necessitates the adoption of advanced energy storage systems such as lithium-ion and flow batteries. These storage systems allow surplus energy generated during peak sunlight or wind periods to be stored and redistributed during periods of low generation, ensuring uninterrupted power supply.

Smart energy management systems (SEMS) act as the central nervous system of the building, leveraging real-time data and AI algorithms to monitor, control and optimize the generation, storage and consumption of energy. This level of control facilitates not only efficient energy use but also adaptive responses to grid demand, time-of-use pricing and environmental conditions. In advanced smart buildings, Smart Energy Management Systems (SEMS) actively integrate with Building Management Systems (BMS) and external power grids to support demand response initiatives, thereby enhancing the overall efficiency of the energy ecosystem. Previous research by Chen et al. (2025) supports this claim, finding that buildings equipped with AI-based SEMS reported not only reduced peak load demand but also enhanced energy security and reliability in smart city contexts. Beyond energy, smart environmental technologies extend to water and waste resource management. Smart water-saving technologies, including intelligent irrigation systems, utilize environmental sensors to adjust water consumption according to real-time weather data and soil moisture levels. This method effectively prevents over utilize water resource and significantly minimizes waste water. Similarly, smart plumbing systems equipped with leak detection sensors can identify and isolate leaks immediately as well as preventing water loss of up to 20% (Romero-Ben et al., 2023; Gupta et al., 2020; El-Zahab & Zayed, 2019), which is particularly critical in regions experiencing water stress. Comparable outcomes, who found that smart plumbing systems reduced annual water consumption in high-rise residential buildings by an average of 18%, especially in drought-prone regions (Zhao et al., 2018).

Smart waste management is another integral component of environmentally responsive building systems. IoT-enabled waste bins equipped with sensors provide continuous data on fill levels, bin orientation and temperature as well as enabling dynamic scheduling of waste collection. These systems minimize unnecessary vehicle movements, reduce fuel usage, decrease greenhouse gas emissions and lower labor expenses (Hussain et al., 2024). Additionally, cutting-edge technologies that employ robotic waste sorting and utilize low-carbon or recycled construction materials actively reinforce circular economy practices and diminish the embodied carbon associated with building development and operation (Dulguun, 2023; Idir et al., 2025; Chauhan et al., 2022). In a comparative analysis, the adoption of intelligent waste management systems in institutional environments resulted in a 28% decline in waste-related expenses and a 15% reduction in carbon emissions, demonstrating cost-effectiveness and sustainability (Lakhouit, 2025; Fang et al., 2023; Fatorachian et al., 2025). Unlike previous isolated methods, the present analysis focuses on integrated system functionality, real-time enhancement and intersectoral efficiency, especially through the integration of AI across the energy, water and waste management subsystems. This study addresses the existing gap in research on the holistic environmental intelligence of smart buildings, policymakers and practitioners to develop comprehensive sustainability frameworks that scale effectively and adapt to both urban and rural environments. In summary, the integration of AI-driven systems across energy, water and waste management in smart buildings enables a unified, efficient and sustainable approach to environmental resource management. By harnessing real-time data and advanced analytics, these intelligent systems optimize operational performance, reduce emissions and support circular economy principles. This comprehensive and interconnected strategy positions smart buildings as key contributors to achieving long-term sustainability and resilience in both urban and rural settings.

3.3. Smart building criteria in social element

The social element emphasizes improving the well-being, comfort and inclusiveness of building occupants. Indoor environmental quality (IEQ) is given priority through real-time tracking of air quality, temperature and humidity as enabled by advanced HVAC systems and IoT sensors. Intelligent HVAC systems sustain ideal thermal conditions while reducing energy usage and air purification systems to identify and eliminate pollutants and enhance indoor air quality (Aghili et al., 2025). As illustrated in Figure 4, comfort, health and safety and security are predominant aspects within the social dimension.

The social dimension of sustainability is often underrepresented compared to its environmental and economic counterparts, despite being equally essential for achieving long-term well-being and inclusive development. Social factors such as comfort, health, user engagement, safety, accessibility and effective communication are central to create environments that uphold human dignity, inclusivity and quality of life (Maidin et al., 2021). A space, system or policy can be truly successful if it accommodates the diverse needs of its users. Comfort and health form the foundation of a balanced and productive life with well-designed physical environments enhancing comfort through adequate ventilation, natural lighting, sound control and thermal regulation. Beyond physical aspects, comfort also includes mental and emotional well-being, as environments that foster relaxation, reduce stress and support psychological health are crucial in both personal and professional settings (Apriyanti et al., 2024). In this regard, human-centric design plays a critical role in creating spaces that promote healthy lifestyles. Moreover, user engagement ensures individuals are actively involved in decisions that impact to users by enhancing the relevance and effectiveness of policies and spaces. Empowering people to express user concerns and preferences increases satisfaction, strengthens community bonds and fosters a sense of ownership. Modern tools such as surveys, public consultations and participatory design models promote meaningful engagement and achieve more inclusive outcomes. Safety is another pillar of social sustainability, involves not only physical protection from harm but also emotional security and cybersecurity (Eizenberg & Jabareen, 2017). Well-lit environments, clear emergency procedures and inclusive safety protocols contribute to a universal sense of security, regardless of age, gender, or ability. In today's digital world, protecting personal data and ensuring safe online spaces are also critical for maintaining trust and upholding social values. Equally important are accessibility and communication, which are foundational to social equity. Accessibility beyond physical infrastructure to include digital inclusion, clear communication of information and the removal of systemic barriers (van Wee, 2022). The effective communication delivered in multiple languages, media formats and technologies ensures that all members of society can access essential services and information. This method enables full participation in community life and helps reduce social disparities (Mittra et al., 2025). Social sustainability is indispensable in designing functional, inclusive and empowering spaces and systems. By prioritizing comfort, safety, engagement and accessibility, contribute to building resilient societies based on statisfaction, trust and a shared sense of belonging.

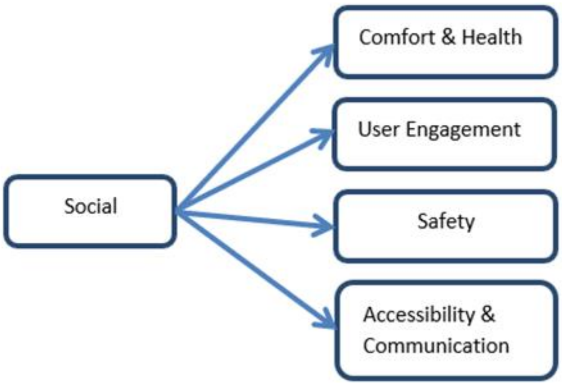

Figure 4 Smart building criteria in social element.

Many researchers agree that the outlined criteria are instrumental in sustaining a high quality of life within built environments. Adaptive thermal comfort systems is driven by Artificial Intelligence (AI) and the Internet of Things (IoT), offer customized temperature regulation based on user preferences and real-time environmental feedback. Thereby optimizing energy consumption while enhancing occupant comfort (Lee & Lee, 2023; Ahsan et al., 2024; Ghahramani et al., 2020). Similarly, smart lighting and acoustic systems substantially improve cognitive performance, concentration and psychological well-being in residential and workplace settings (Song & Calautit, 2024; Melikoğlu, 2024; Soheilian et al., 2021). Inclusivity in smart buildings through universal design principles that ensure accessibility for users of all physical abilities. Integrating AI-driven vertical mobility devices, including elevators and escalators, it enhances ease of movement and safety for older adults and those with physical or cognitive challenges (Jain et al., 2025). Moreover, biophilic design is a concept that incorporates natural elements into architectural space. It has been a relationship with reduced stress, improved mood and increased productivity among occupants (Alam, 2023; Asojo & Hazazi, 2025). Combining wellness-oriented architecture with intelligent automation enables smart buildings to act as holistic environments that support mental, emotional and physical health. Lv & Sarker (2024) emphasize that such integration not only enhances workplace efficiency but also contributes to mental resilience in urban populations. Studies by Sleiman et al. (2024) further confirm that occupant-centric smart environments contribute to long-term health benefits and stress reduction.

Safety and emergency preparedness are integral components of smart building systems. Smart surveillance, facial recognition and motion detection technologies enable real-time security monitoring and prevent unauthorized access (punith et al., 2024). Advanced emergency response systems utilize sensor-based data to detect critical incidents such as fires, earthquakes, or toxic gas leaks and automatically initiate evacuation protocols through mobile notifications and dynamic signage (Sharma et al., 2025; Sun et al., 2025). These systems significantly enhance situational awareness and response time, as noted by Shaharuddin et al. (2023), which highlights the effectiveness in reducing injury and damage during emergencies. Furthermore, IoT-enabled platforms facilitate social engagement and environmental awareness among occupants. By offering real-time data through mobile applications and dashboards, users can monitor and optimize energy usage, indoor air quality, temperature, lighting and humidity levels. This active engagement enhances energy efficiency and user satisfaction, as demonstrated in studies by Almudayni et al. (2025) and Poyyamozhi et al. (2024). Chen et al. (2012) found that interactive feedback mechanisms, such as goal-based energy cost reduction prompts, effectively influence sustainable behavior and long-term energy conservation.

In conclusion, the integration of intelligent technologies with user-centered design in smart buildings not only improves functionality and safety but also promotes health, inclusivity and environmental responsibility. Recent empirical studies strongly support the claim that smart buildings play an important role in enhancing modern lifestyles through technology-driven, sustainable solutions. This study contributes to the growing body of knowledge on smart building systems by offering an integrated perspective that combines environmental comfort, safety, inclusivity and user engagement within a single holistic framework. While existing studies often focus on isolated elements, such as energy efficiency, security and indoor air quality but this research emphasizes the interconnected nature of intelligent systems. It highlights the cumulative impact on occupant well-being and building performance. By synthesizing insights from diverse fields, including architecture, engineering, human-computer interaction and sustainability science, the study provides a multi-dimensional approach that supports the development of more resilient and user-centered smart environments.

3.4. Smart building criteria in governance element

The governance element in smart building development plays an important role in ensuring compliance with legal regulations, industry certifications and ethical standards. While fostering stakeholder collaboration, data privacy and transparent decision-making. Effective governance in this context not only ensures regulatory compliance but also establishes the trust and accountability needed to sustain and strengthen smart infrastructure systems over the long term (Wolniak, & Stecuła, 2024; Yin & Song, 2023). Policy compliance in smart building governance have several critical dimensions, including energy efficiency, safety standards, cybersecurity and interoperability within broader smart city ecosystems. In Malaysia, building energy performance is regulated by standards such as MS1525:2019, which outlines recommended practices for enhancing energy efficiency in non-residential buildings. Additionally, the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) sets international benchmarks that optimize HVAC systems and promote sustainable building performance. A study by Shari et al. (2023) highlighted that high-rise government office buildings in Malaysia recorded an average Building Energy Intensity (BEI) of 161 kWh/m^2/year, exceeding Green Building Index (GBI) targets. Through a calibrated energy simulation approach, identified optimal retrofit strategies for building envelopes, achieving annual energy savings of 4% to 7%, which aligns with the standards of the Green Building Index (GBI) and the Economic Planning Unit (EPU) (Shari et al., 2023). Recent research highlights how integrated energy management systems effectively reduce energy waste, enhance occupant comfort and advance smart building capabilities (Bayasgalan et el., 2024; Hakawati et al., 2024).

Despite rapid technological advancements, Malaysia still lacks a dedicated national framework for smart buildings. This gap is a barrier for systematic and integrated implementation. UL Solutions is a global leader in applied safety science and developed the SPIRE program. Similarly, the European Union (EU) and SmartScore introduced the Smart Readiness Indicator (SRI) and SmartScore certifications, respectively. These organizations jointly develop internationally recognized certification systems and offer comprehensive frameworks to assess the smart capabilities of buildings. These frameworks are essential for performance benchmarking, guiding investment decisions and ensuring interoperability across digital platforms (Delavar et al., 2025; Siddique et al., 2023; Martínez et al., 2021). One of the most crucial concerns in smart building governance is cybersecurity. Given the interconnected nature of IoT-based systems, smart buildings are inherently vulnerable to cyber threats, including device misconfigurations, the absence of standardized security protocols and insider threats. Without robust cybersecurity strategies, even the most advanced buildings remain at risk. To address this, comprehensive cybersecurity frameworks must incorporate multi-factor authentication, end-to-end encryption, real-time threat detection, and regular security audits. Achaal et al. (2024) emphasized that these measures are essential for safeguarding user data, protecting digital infrastructures and ensuring compliance with global data protection standards, such as the General Data Protection Regulation (GDPR) (Achaal et al., 2024). Moreover, current literature stresses the need to incorporate AI-based threat intelligence systems to strengthen cyber-resilience in smart environments (Alsulami, 2024).

Performance monitoring and data analytics drive smart building governance by enabling predictive maintenance, analyzing occupant behavior and optimizing energy efficiency. However, the complexity and large scale of modern smart buildings make manual monitoring impractical. Instead, the deployment of AI-driven systems and IoT sensors provides real-time insights that empower data-informed decisions aligned with sustainability objectives. Studies have shown that data-centric decision models significantly enhance operational efficiency and reduce resource consumption in intelligent buildings (Billanes et al., 2025).

Figure 5 illustrates how governance actively drives the development and implementation of smart infrastructure and sustainable building systems. It exerts its influence through two interrelated components which are data management and policy-practice alignment. Firstly, robust governance frameworks support the creation of comprehensive data management systems that oversee data collection, storage, security and analytics in a systematic and integrated manner. This structured system provides operational insight and strengthens the credibility of governance practices. At the same time, it improves the precision and effectiveness of energy monitoring and performance optimization in smart building environments. Secondly, governance serves as the driving force behind the formulation and execution of strategic policies. Policies rooted in strong governance frameworks provide the necessary standards, regulatory mechanisms and implementation strategies that guide the deployment of smart technologies. Policy plays an important role in defining energy efficiency objectives and ensuring the protection of occupant well-being. Ultimately, effective governance ensures that data-driven decision-making and policy implementation are harmonized, thereby enabling smart infrastructure systems that are not only efficient and sustainable but also resilient and adaptive to changing needs.

The integration of digital twin technologies in energy performance monitoring significantly enhances governance by supporting continuous oversight and enabling informed as well as data-driven decision-making processes. At the core of this transformation lies effective data management, which serves as a critical enabler for smart buildings. Through the seamless integration of smart platforms, these systems facilitate comprehensive data collection, energy optimization and autonomous operational adjustments. These platforms harness the power of IoT devices and sensor networks to collect real-time data on a wide range of parameters, including energy consumption patterns, environmental conditions and occupant behaviors. Detailed and real-time data enable intelligent control systems to adaptively manage Heating, Ventilation and Air Conditioning (HVAC) functionalities, lighting in response to occupancy patterns and daylight integration to maximize energy performance while maintaining occupant comfort (Omole et al., 2024; Toyibah Masyhur et al., 2024; Yao et al., 2023). Furthermore, the use of centralized, intelligent platforms promotes transparency and accountability in building management. By providing building managers with an integrated and real-time overview of energy usage and operational performance, these platforms support more accurate maintenance planning, resource allocation and progress tracking against sustainability benchmarks (Hauashdh et al., 2024; Kozlovska et al., 2023). These are to facilitate predictive maintenance and proactive interventions, reducing operational costs and extend asset life cycles. In summary, the integration of digital twin technologies and intelligent data platforms in energy performance monitoring empowers smart building governance through real-time insights, predictive capabilities and adaptive control. This not only optimizes energy efficiency and occupant comfort but also enhances transparency, reduces operational costs and supports long-term sustainability goals.

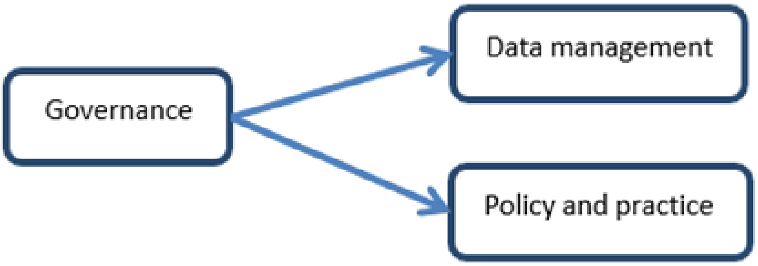

Figure 5 Smart building criteria in government element.

4. Conclusion and Recommendation

The focus of key environmental priorities such as water conservation, energy efficiency, carbon emission reduction and waste management with the use of advanced technologies has ushered in a new era of sustainability through the development of smart buildings. This integrated approach not only addresses critical environmental challenges but also enhances operational efficiency, resilience and the capacity to adapt to changing conditions. Smart technologies, including Artificial Intelligence (AI), the Internet of Things (IoT) and Smart Energy Management Systems (SEMS), have proven to be highly effective in optimizing resource use, minimizing waste and reducing the environmental footprint of building operations. The implementation of predictive analytics, real-time monitoring and renewable energy systems further reinforces the potential of smart infrastructure to meet global climate goals, including those outlined in the Paris Agreement. By leveraging the synergies across sectors such as energy, water and waste management, smart buildings offer a viable and scalable solution for achieving net-zero emissions and advancing sustainable development. However, the successful adoption of these technologies depends heavily on the establishment of supportive policy frameworks, active stakeholder engagement and the continuous integration of intelligent systems that can evolve in response to both environmental and societal needs. To promote the widespread adoption of smart environmental technologies, governments should introduce and enforce comprehensive policies that support both the construction of new buildings and the retrofitting of existing infrastructure. These efforts should be complemented by incentives such as tax reliefs, financial subsidies and certification programs, all of which can accelerate the transformation toward sustainable construction practices. Stakeholders, including private sector investors and building operators, should prioritize investments in AI-driven infrastructure, particularly in smart energy and water management systems. These systems offer advanced predictive capabilities that enhance efficiency, reduce operational costs and contribute significantly to lowering carbon emissions while improving national energy security.

Furthermore, building developers and urban planners should be encouraged to integrate renewable energy sources such as photovoltaic (PV) solar panels, wind turbines and hybrid systems. These efforts will reduce dependence on conventional energy sources and promote long-term energy autonomy. To address the intermittent nature of renewable energy generation, it is essential to expand the development and deployment of advanced energy storage technologies such as lithium-ion and flow batteries, which ensure a stable and uninterrupted energy supply. In parallel, waste management systems should be restructured in alignment with circular economy principles that emphasize the reuse and recycling of materials and the use of low-carbon construction alternatives. The adoption of robotic waste sorting and IoT-enabled waste tracking can further enhance the efficiency and sustainability of waste management. Another important recommendation is the implementation of real-time monitoring and data analytics across all environmental subsystems. The use of IoT and SEMS for continuous monitoring enables prompt responses to inefficiencies and system failures, ensuring optimal resource management. Raising public awareness and providing targeted training programs are equally essential. These initiatives can help educate building occupants and facility managers about sustainable practices, leading to behavioral changes that support system performance. Lastly, policymakers and practitioners should collaborate to develop a holistic sustainability framework that guides the design, deployment and evaluation of smart building systems. This framework should be adaptable to a wide range of settings, including both urban and rural areas, to promote inclusive and scalable environmental progress.

This study makes a valuable contribution by thoroughly exploring how Artificial Intelligence (AI) and Internet of Things (IoT) technologies efficiently manage building functions, encourage eco-friendly practices and improve the overall well-being of all users, including at-risk groups such as older adults and those with physical or cognitive challenges. It underscores the importance of implementing flexible and universally accessible design approaches and delivering practical, evidence-based suggestions for integrating intelligent technologies that comply with universal design principles and aspects of nature-inspired (biophilic) architecture. Additionally, the study demonstrates how real-time data and user input systems play a crucial role in enhancing energy conservation, elevating occupant comfort and reinforcing safety measures. The significance of these findings lies in the practical application for policymakers, architects, developers and urban planners who aim to design smart buildings that are not only technologically advanced but also socially responsible and environmentally sustainable. As cities worldwide move toward digital transformation and urban resilience, the insights from this study offer a strategic framework for integrating smart building features into national development agendas, especially in the context of smart cities and green building initiatives. Moreover, the findings are particularly relevant in the post-pandemic era, where indoor environmental quality and health-focused design have become priorities. The research accentuates how smart environments contribute to physical and cognitive health maintenance, public safety management and the development of responsive environments that adapt to the evolving needs of the occupants. By advancing knowledge in this domain, the study also opens pathways for future research on human-centered smart technologies, data-driven sustainability models and the socio-technical dynamics of intelligent urban infrastructure.

From a governance perspective, digital twins not only foster smart building operations but also align with broader sustainability and policy goals by offering verifiable metrics and performance indicators. Thus, these technologies do not merely serve a functional role but also act as enablers of systemic transformation in how buildings are managed and regulated. Governance plays a crucial role in driving the development and implementation of smart infrastructure and sustainable building systems through two key components including data management and policy-practice alignment. Strong governance frameworks actively establish and support comprehensive data management systems that systematically and integrally collect, store, secure and analyze data. These frameworks enhance the accuracy and effectiveness of energy monitoring while strengthening the credibility and transparency of smart building management. Moreover, governance actively formulates and enforces policies that set standards and regulatory mechanisms to guide energy efficiency goals and ensure occupant well-being. The integration of digital twin technology significantly reinforces governance by enabling continuous oversight and data-driven decision-making. Connected devices and sensor arrays empower smart platforms to monitor real-time data, facilitating self-directed management of HVAC, lighting and environmental factors for improved energy efficiency and occupant well-being. Centralized intelligent platforms promote transparency and accountability by enabling more precise maintenance planning and proactive interventions, which reduce operational costs and extend asset lifespans. In conclusion, strong governance coupled with the implementation of digital twin technologies enhances not only energy efficiency and operational effectiveness but also advances wider sustainability and regulatory goals. This strategy enables a fundamental shift in building management and oversight, rendering buildings more efficient, eco-friendly and responsive to evolving future demands. Therefore, continuous emphasis on developing robust governance frameworks and smart technology integration is essential for the successful advancement of sustainable smart infrastructure and smart cities.

Acknowledgment

This research was supported by Universiti Tun Hussein Onn Malaysia (UTHM) through Tier 1 (vot Q950).

Ethical Considerations

Not applicable.

Conflict of Interest

The authors declare no conflicts of interest.

Funding

This research received financial support from Universiti Tun Hussein Onn Malaysia (UTHM) through Tier 1 (vot Q950).

References

Achaal, B., Adda, M., Berger, M., Ibrahim, H., & Awde, A. (2024). Study of smart grid cyber-security, examining architectures, communication networks, cyber-attacks, countermeasure techniques, and challenges. *Cybersecurity, 7*(10). https://doi.org/10.1186/s42400-023-00200-w

Aghili, S. A., Haji Mohammad Rezaei, A., Tafazzoli, M., Khanzadi, M., & Rahbar, M. (2025). Artificial intelligence approaches to energy management in HVAC systems: A systematic review. *Buildings, 15*(7), 1008. https://doi.org/10.3390/buildings15071008

Ahsan, M., Shahzad, W., & Arif, K. M. (2024). AI-based controls for thermal comfort in adaptable buildings: A review. *Buildings, 14*(11), 3519. https://doi.org/10.3390/buildings14113519

Akhtar, F., Senadjki, A., & Vija Kumaran, V. (2025). Sustainability meets digital culture: The influence of ESG on financial performance in Malaysian manufacturing SMEs. *Journal of Innovative Digital Transformation, 2*(1), 90–108. https://doi.org/10.1108/JIDT-10-2024-0031

Alahi, M. E. E., Sukkuea, A., Tina, F. W., Nag, A., Kurdthongmee, W., Suwannarat, K., & Mukhopadhyay, S. C. (2023). Integration of IoT-enabled technologies and artificial intelligence (AI) for smart city scenario: Recent advancements and future trends. *Sensors (Basel, Switzerland), 23*(11), 5206. https://doi.org/10.3390/s23115206

Alam, M. (2023). Biophilic architecture and designs for mental well-being. *IOP Conference Series: Earth and Environmental Science, 1218*(1), 012020. IOP Publishing. https://doi.org/10.1088/1755-1315/1218/1/012020

Aldowaish, A., Kokuryo, J., Almazyad, O., & Goi, H. C. (2022). Environmental, social, and governance integration into the business model: Literature review and research agenda. *Sustainability, 14*(5), 2959. https://doi.org/10.3390/su14052959

Almudayni, Z., Soh, B., Samra, H., & Li, A. (2025). Energy inefficiency in IoT networks: Causes, impact, and a strategic framework for sustainable optimisation. *Electronics, 14*(1), 159. https://doi.org/10.3390/electronics14010159

Alsulami, M. H. (2024). An AI-driven model to enhance sustainability for the detection of cyber threats in IoT environments. *Sensors, 24*(22), 7179. https://doi.org/10.3390/s24227179

Apriyanti, R., Hayuningsih, S., & Firdaus, M. F. (2024). The relationship between physical, psychological health and space comfort in the elderly: A qualitative study. *Asian Journal of Engineering, Social and Health, 3*(9), 2133–2140. https://doi.org/10.46799/ajesh.v3i9.447

Asojo, A., & Hazazi, F. (2025). Biophilic design strategies and indoor environmental quality: A case study. *Sustainability, 17*(5), 1816. https://doi.org/10.3390/su17051816

Bayasgalan, A., Park, Y. S., Koh, S. B., & Son, S.-Y. (2024). Comprehensive review of building energy management models: Grid-interactive efficient building perspective. *Energies, 17*(19), 4794. https://doi.org/10.3390/en17194794

Billanes, J. D., Ma, Z. G., & Jørgensen, B. N. (2025). Data-driven technologies for energy optimization in smart buildings: A scoping review. *Energies, 18*(2), 290. https://doi.org/10.3390/en18020290

Castro-Lacouture, D. (2023). Construction automation and smart buildings. In S. Y. Nof (Ed.), *Springer handbook of automation* (pp. 1035–1053). Springer International Publishing. https://doi.org/10.1007/978-3-030-96729-1_48

Chao, C. (2013). Smart green buildings of tomorrow. *Indoor and Built Environment, 22*(4), 595–597. https://doi.org/10.1177/1420326X13494617

Chauhan, C., Parida, V., & Dhir, A. (2022). Linking circular economy and digitalisation technologies: A systematic literature review of past achievements and future promises. *Technological Forecasting and Social Change, 177,* 121508. https://doi.org/10.1016/j.techfore.2022.121508

Chen, B., Ye, X., & Dai, F. (2025). Research on sustainable building development in the context of smart cities: Based on CiteSpace, VOSviewer, and Bibliometrix. *Buildings, 15*(11), 1811. https://doi.org/10.3390/buildings15111811

Chen, C., Zhang, J., & Liang, J. (2021). Mapping the intellectual structure of smart cities research: A bibliometric analysis. *Sustainable Cities and Society, 64,* 102537. https://doi.org/10.1016/j.scs.2020.102537

Chen, D., & Lai, H. W. (2023). Water and climate change. In *Routledge handbook of water and development* (pp. 250–262). Taylor & Francis. https://doi.org/10.4324/9781003095545-28

Chen, H. M., Lin, C. W., Hsieh, S. H., Chao, H. F., Chen, C. S., Shiu, R. S., Ye, S. R., & Deng, Y. C. (2012). Persuasive feedback model for inducing energy conservation behaviors of building users based on interaction with a virtual object. *Energy and Buildings, 45,* 106–115. https://doi.org/10.1016/j.enbuild.2011.10.029

Chopra, S. S., Senadheera, S. S., Dissanayake, P. D., Withana, P. A., Chib, R., Rhee, J. H., & Ok, Y. S. (2024). Navigating the challenges of environmental, social, and governance (ESG) reporting: The path to broader sustainable development. *Sustainability, 16*(2), 606. https://doi.org/10.3390/su16020606

Delavar, T., Borgentorp, E., & Junnila, S. (2025). The smart buildings revolution: A comprehensive review of the smart readiness indicator literature. *Applied Sciences, 15*(4), 1808. https://doi.org/10.3390/app15041808

Dulguun, E. (2023). Implementation of cutting-edge technologies in facility management: Challenges and opportunities in the digital era. *Journal Dimensie Management and Public Sector, 4*(4), 24–33. https://doi.org/10.48173/jdmps.v4i4.243

Eizenberg, E., & Jabareen, Y. (2017). Social sustainability: A new conceptual framework. *Sustainability, 9*(1), 68. https://doi.org/10.3390/su9010068

El Moll, A. (2023). Water resources and climate change: Regional, national and international perspective. In M. N. Vara Prasad & M. B. T. Smol (Eds.), *Sustainable and circular management of resources and waste towards a Green Deal* (pp. 309–336). Elsevier. https://doi.org/10.1016/B978-0-323-95278-1.00010-3

El-Zahab, S., & Zayed, T. (2019). Leak detection in water distribution networks: An introductory overview. *Smart Water, 4*(1), 5. https://doi.org/10.1186/s40713-019-0017-x

Falkner, R. (2016). The Paris Agreement and the new logic of international climate politics. *International Affairs, 92*(5), 1107–1125. https://doi.org/10.1111/1468-2346.12708

Fang, B., Yu, J., Chen, Z., Osman, A. I., Farghali, M., Ihara, I., Hamza, E. H., Rooney, D. W., & Yap, P. S. (2023). Artificial intelligence for waste management in smart cities: A review. *Environmental Chemistry Letters, 21*(4), 1959–1989. https://doi.org/10.1007/s10311-023-01604-3

Fatorachian, H., Kazemi, H., & Pawar, K. (2025). Digital technologies in food supply chain waste management: A case study on sustainable practices in smart cities. *Sustainability, 17*(5), 1996. https://doi.org/10.3390/su17051996

Ghahramani, A., Galicia, P., Lehrer, D., Varghese, Z., Wang, Z., & Pandit, Y. (2020). Artificial intelligence for efficient thermal comfort systems: Requirements, current applications and future directions. *Frontiers in Built Environment, 6,* 49. https://doi.org/10.3389/fbuil.2020.00049

Goel, A., Masurkar, S., & Pathade, G. R. (2024). An overview of digital transformation and environmental sustainability: Threats, opportunities, and solutions. *Sustainability, 16*(24), 11079. https://doi.org/10.3390/su162411079

Gupta, A. D., Pandey, P., Feijóo, A., Yaseen, Z. M., & Bokde, N. D. (2020). Smart water technology for efficient water resource management: A review. *Energies, 13*(23), 6268. https://doi.org/10.3390/en13236268

Hakawati, B., Mousa, A., & Draidi, F. (2024). Smart energy management in residential buildings: The impact of knowledge and behavior. *Scientific Reports, 14,* 1702. https://doi.org/10.1038/s41598-024-51638-y

Hauashdh, A., Nagapan, S., Jailan, J., & Gamil, Y. (2024). An integrated framework for sustainable and efficient building maintenance operations aligning with climate change, SDGs, and emerging technology. *Results in Engineering, 21,* 101822. https://doi.org/10.1016/j.rineng.2024.101822

Hussain, I., Elomri, A., Kerbache, L., & El Omri, A. (2024). Smart city solutions: Comparative analysis of waste management models in IoT-enabled environments using multiagent simulation. *Sustainable Cities and Society, 103,* 105247. https://doi.org/10.1016/j.scs.2024.105247

Idir, R., Djerbi, A., & Tazi, N. (2025). Optimising the circular economy for construction and demolition waste management in Europe: Best practices, innovations and regulatory avenues. *Sustainability, 17*(8), 3586. https://doi.org/10.3390/su17083586

Jain, V., Mitra, A., & Haque, A. (2025). Integrating AI in assistive devices for cognitive support in the elderly: Design, usability, and ethical frameworks. In B. Gupta, D. Pramod, & M. Moslehpour (Eds.), *Sustainable information security in the age of AI and green computing* (pp. 547–566). IGI Global. https://doi.org/10.4018/979-8-3693-8034-5.ch027

Kaiser, Z. R. M. A. (2024). Smart governance for smart cities and nations. *Journal of Economy and Technology, 2,* 216–234. https://doi.org/10.1016/j.ject.2024.07.003

Kanasan, V., & Hassan, M. S. (2023). Challenges in addressing green growth in Malaysian cities. In I. Pal, R. Shaw, T. Ichinose, Yonariza, & T. Oda (Eds.), *Proceedings of the 2nd International Symposium on Disaster Resilience and Sustainable Development* (pp. 89–104). Springer Nature Singapore.

Karoon, K. A., Ibraheem, Y., & Piroozfar, P. (2025). Improving energy performance in smart buildings through information and communication technology: A state-of-the-art review. *Journal of Engineering and Sustainable Development, 29*(3), 297–309. https://doi.org/10.31272/jeasd.2550

Khan, M. A., Farooq, M. S., Saleem, M., Shahzad, T., Ahmad, M., Abbas, S., & Abu-Mahfouz, A. M. (2025). Smart buildings: Federated learning-driven secure, transparent and smart energy management system using XAI. *Energy Reports, 13,* 2066–2081. https://doi.org/10.1016/j.egyr.2025.01.063

Kim, D., & Jeong, Y. (2025). The role of ESG activities in strengthening fan trust and loyalty: A societal perspective on sustainable sports business. *Societies, 15*(5), 119. https://doi.org/10.3390/soc15050119

Kozlovska, M., Petkanic, S., Vranay, F., & Vranay, D. (2023). Enhancing energy efficiency and building performance through BEMS-BIM integration. *Energies, 16*(17), 6327. https://doi.org/10.3390/en16176327

Kuok Ho, D. T. (2023). A review of environmental, social and governance (ESG) regulatory frameworks: Their implications on Malaysia. *Tropical Aquatic and Soil Pollution, 3,* 168–183. https://doi.org/10.53623/tasp.v3i2.282

Kwilinski, A., Lyulyov, O., & Pimonenko, T. (2024). Reducing transport sector CO2 emissions patterns: Environmental technologies and renewable energy. *Journal of Open Innovation: Technology, Market, and Complexity, 10*(1), 100217. https://doi.org/10.1016/j.joitmc.2024.100217

Lakhouit, A. (2025). Revolutionizing urban solid waste management with AI and IoT: A review of smart solutions for waste collection, sorting, and recycling. *Results in Engineering, 25,* 104018. https://doi.org/10.1016/j.rineng.2025.104018

Lee, D. S., Chen, Y. T., & Chao, S. H. (2022). Universal workflow of artificial intelligence for energy saving. *Energy Reports, 8,* 1602–1633. https://doi.org/10.1016/j.egyr.2021.12.066

Lee, D., & Lee, S. T. (2023). Artificial intelligence enabled energy-efficient heating, ventilation and air conditioning system: Design, analysis and necessary hardware upgrades. *Applied Thermal Engineering, 235,* 121253. https://doi.org/10.1016/j.applthermaleng.2023.121253

Lv, Y., & Sarker, M. N. I. (2024). Integrative approaches to urban resilience: Evaluating the efficacy of resilience strategies in mitigating climate change vulnerabilities. *Heliyon, 10*(6), e28191. https://doi.org/10.1016/j.heliyon.2024.e28191

Maidin, M. A. A., Ahmad, F., Abidin, N. I., Suhaili, J., Awang, M., Rahman, M. A. A., Musa, M. K., Hamidon, N., Yusop, F. M., Syafiq Syazwan, M. M., Harun, H., Hamid, N. H. A., & Kamil, N. A. (2021). Design campus map using OpenStreetMap digital software. In M. A. A. Zaini, M. Jusoh, & N. Othman (Eds.), *Proceedings of the 3rd International Conference on Separation Technology* (pp. 113–129). Springer Singapore.

Maka, A. O. M., Ghalut, T., & Elsaye, E. (2024). The pathway towards decarbonisation and net-zero emissions by 2050: The role of solar energy technology. *Green Technologies and Sustainability, 2*(3), 100107. https://doi.org/10.1016/j.grets.2024.100107

Martínez, I., Zalba, B., Trillo-Lado, R., Blanco, T., Cambra, D., & Casas, R. (2021). Internet of Things (IoT) as sustainable development goals (SDG) enabling technology towards smart readiness indicators (SRI) for university buildings. *Sustainability, 13*(14), 7647. https://doi.org/10.3390/su13147647

Mayouf, M., Afsar, F., Iqbal, A., Javidroozi, V., & Mohandes, S. R. (2024). Synergies between digital construction technologies in smart buildings and smart city development to meet building users' expectations. *Heliyon, 10*(8), e28585. https://doi.org/10.1016/j.heliyon.2024.e28585

Melikoğlu, Y. (2024). The impact of architectural workspaces supported by artificial intelligence on psychological productivity. *Anatolian Journal of Mental Health, 1*(2), 50–74. https://doi.org/10.5281/zenodo.13765920

Ministry of Housing and Local Government. (2018). *Malaysia smart city framework.* https://www.kpkt.gov.my/index.php/pages/view/675

Mittra, G., Rahul, M., & Mehta, G. (2025). Social sustainability: A catalyst for employee well-being and safety culture of an organization. *International Journal of Research in Human Resource Management, 7*(1), 63–69. https://doi.org/10.33545/26633213.2025.v7.i1a.258

Mustapha, Z., Akomah, B., Abilgah, T., & Tieru, C. K. (2025). Enhancing energy efficiency and management in smart buildings: A holistic approach. *Journal of Applied Science and Technology Trends, 6*(1), 16–24. https://doi.org/10.38094/jastt61206

National Digital Department. (2024). *Malaysia smart city framework (MSCF).* https://www.malaysia.gov.my/portal/content/30947

Nguyen, T. H., Nguyen, T. T., & Pham, H. T. (2022). ESG integration in smart buildings: A systematic bibliometric and content analysis. *Journal of Cleaner Production, 375,* 134122. https://doi.org/10.1016/j.jclepro.2022.134122

Olatunde, T., Okwandu, A., Akande, D. O., & Sikhakhane, Z. Q. (2024). Review of energy-efficient HVAC technologies for sustainable buildings. *International Journal of Science and Technology Research Archive, 6,* 12–20. https://doi.org/10.53771/ijstra.2024.6.2.0039

Omole, F. O., Olajiga, O. K., & Olatunde, T. M. (2024). Sustainable urban design: A review of eco-friendly building practices and community impact. *Engineering Science & Technology Journal, 5*(3), 1020–1030. https://doi.org/10.51594/estj.v5i3.955

Orikpete, O. F., Ikemba, S., & Ewim, D. R. E. (2023). Integration of renewable energy technologies in smart building design for enhanced energy efficiency and self-sufficiency. *The Journal of Engineering and Exact Sciences, 9*(9), 16423-01e. https://doi.org/10.18540/jcecvl9iss9pp16423-01e

Page, M. J., McKenzie, J. E., Kirkham, J., Dwan, K., Kramer, S., Green, S., & Forbes, A. (2014). Bias due to selective inclusion and reporting of outcomes and analyses in systematic reviews of randomised trials of healthcare interventions. *Cochrane Database of Systematic Reviews, 2014*(10), MR000035. https://doi.org/10.1002/14651858.MR000035.pub2

Poyyamozhi, M., Murugesan, B., Rajamanickam, N., Shorfuzzaman, M., & Aboelmagd, Y. (2024). IoT—A promising solution to energy management in smart buildings: A systematic review, applications, barriers, and future scope. *Buildings, 14*(11), 3446. https://doi.org/10.3390/buildings14113446

Punith, M. S., Mamatha, I., & Tripathi, S. (2024). Home intrusion: Smart security and live video surveillance system. *Engineering Research Express, 6*(4), 045001. https://doi.org/10.1088/2631-8695/ad9fd7

Rane, N. (2023). Integrating leading-edge artificial intelligence (AI), internet of things (IoT), and big data technologies for smart and sustainable architecture, engineering and construction (AEC) industry: Challenges and future directions. *SSRN Electronic Journal.* https://doi.org/10.2139/ssrn.4616049

Rehman, A. U., Wadud, Z., Elavarasan, R. M., Hafeez, G., Khan, I., Shafiq, Z., & Alhelou, H. H. (2021). An optimal power usage scheduling in smart grid integrated with renewable energy sources for energy management. *IEEE Access, 9*, 84619–84638. https://doi.org/10.1109/ACCESS.2021.3087321

Romero-Ben, L., Alves, D., Blesa, J., Cembrano, G., Puig, V., & Duviella, E. (2023). Leak detection and localization in water distribution networks: Review and perspective. *Annual Reviews in Control, 55,* 392–419. https://doi.org/10.1016/j.arcontrol.2023.03.012

Sadiq, M., Ngo, T. Q., Pantamee, A. A., Khudoykulov, K., Thi Ngan, T., & Tan, L. P. (2022). The role of environmental social and governance in achieving sustainable development goals: Evidence from ASEAN countries. *Economic Research-Ekonomska Istraživanja, 36*(1), 170–190. https://doi.org/10.1080/1331677X.2022.2072357

Shafiullah, M., Rahman, S., Imteyaz, B., Aroua, M. K., Hossain, M. I., & Rahman, S. M. (2023). Review of smart city energy modeling in Southeast Asia. *Smart Cities, 6*(1), 72–99. https://doi.org/10.3390/smartcities6010005

Shah, S. A. A., Khan, M. A., & Ahmad, W. (2023). Smart building technologies and sustainability: A bibliometric review. *Energy Reports, 9,* 1234–1249. https://doi.org/10.1016/j.egyr.2023.01.006

Shaharuddin, S., Abdul Maulud, K. N., Abdul Rahman, S. A. F. S., Che Ani, A. I. C., & Pradhan, B. B. (2023). The role of IoT sensor in smart building context for indoor fire hazard scenario: A systematic review of interdisciplinary articles. *Internet of Things, 22,* 100803. https://doi.org/10.1016/j.iot.2023.100803

Shao, J., & Min, B. (2025). Sustainable development strategies for smart cities: Review and development framework. *Cities, 158,* 105663. https://doi.org/10.1016/j.cities.2024.105663

Shari, Z., Mohamad, N. L., & Dahlan, N. D. (2023). Building envelope retrofit for energy savings in Malaysian government high-rise offices: A calibrated energy simulation. *Jurnal Teknologi, 85*(4), 1–15. https://doi.org/10.11113/jurnalteknologi.v85.15124

Sharma, M. L., Kumar, S., Tripathi, K. C., Chaurasia, A., & Kumar, V. (2025). AI-powered smart building evacuation system using IoT. *International Research Journal of Modernization in Engineering Technology and Science, 7*(4), 245–252. https://doi.org/10.56726/IRJMETS74145

Siddique, M. T., Koukaras, P., Ioannidis, D., & Tjortjis, C. (2023). SmartBuild RecSys: A recommendation system based on the Smart Readiness Indicator for energy efficiency in buildings. *Algorithms*, *16*(10), 482. https://doi.org/10.3390/a16100482

Singh, G. (2025). Wearable IoT (w-IoT) artificial intelligence (AI) solution for sustainable smart-healthcare. *International Journal of Information Management Data Insights*, *5*(1), 100291. https://doi.org/10.1016/j.jjimei.2025.100291

Sinha, R. (2024). The role of Internet of Things (IoT) in transforming facilities management in smart cities. *International Journal for Global Academic & Scientific Research, 3*(2), 36–47. https://doi.org/10.55938/ijgasr.v3i2.76

Sleiman, S., Ouf, M., Luo, W., Kramer, R., Zeiler, W., Borkowski, E., Hong, T., Nagy, Z., & Chen, Z. (2024). Overview of occupant-centric KPIs for building performance and their value to various building stakeholders. *Energy and Buildings*, *114704*. https://doi.org/10.1016/j.enbuild.2024.114704

Soheilian, M., Fischl, G., & Aries, M. (2021). Smart lighting application for energy saving and user well-being in the residential environment. *Sustainability*, *13*(11), 6198. https://doi.org/10.3390/su13116198

Song, W., & Calautit, J. K. (2024). Inclusive comfort: A review of techniques for monitoring thermal comfort among individuals with the inability to provide accurate subjective feedback. *Building and Environment*, *257*, 111463. https://doi.org/10.1016/j.buildenv.2024.111463

Sun, H., Xu, R., Luo, J., & Cheng, H. (2025). Review of the application of UAV edge computing in fire rescue. *Sensors*, *25*(11), 3304. https://doi.org/10.3390/s25113304

Taboada-Orozco, A., Yetongnon, K., & Nicolle, C. (2024). Smart buildings: A comprehensive systematic literature review on data-driven building management systems. *Sensors*, *24*(13), 4405. https://doi.org/10.3390/s24134405

Toyibah Masyhur, R., Alias, A. H., Haron, N. A., & Zulkafli, Z. (2024). A systematic review on green practices in the Malaysian construction industry: Status, challenges, key motivations, rating systems and technology evolution. *Energy and Buildings, 114550*. https://doi.org/10.1016/j.enbuild.2024.114550

UL Solutions. (2023). *SPIRE™ qualification program*. UL. https://www.ul.com/services/spire-qualification-program

Valencia-Arias, A., Martínez Rojas, E., Pineda, V. G., Agudelo-Ceballos, E., Rodriguez, L. R. C., Requejo, C. C. E., Cardona-Acevedo, S., Londoño-Celi, W., & Adan, T. E. A. (2025). Research trends on sustainable development in smart cities. *Discover Sustainability*, *6*, 369. https://doi.org/10.1007/s43621-025-01210-z

Van Eck, N. J., & Waltman, L. (2010). Software survey: VOSviewer, a computer program for bibliometric mapping. *Scientometrics*, *84*(2), 523–538. https://doi.org/10.1007/s11192-009-0146-3

van Wee, B. (2022). Accessibility and equity: A conceptual framework and research agenda. *Journal of Transport Geography, 104*, 103421. https://doi.org/10.1016/j.jtrangeo.2022.103421

Vergara-Araya, M., Lehn, H., & Poganietz, W.-R. (2020). Integrated water, waste and energy management systems – A case study from Curauma, Chile. *Resources, Conservation and Recycling, 156*, 104725. https://doi.org/10.1016/j.resconrec.2020.104725

Wei, Y., Yuan, H., & Li, H. (2024). Exploring the contribution of advanced systems in smart city development for the regeneration of urban industrial heritage. *Buildings*, *14*(3), 583. https://doi.org/10.3390/buildings14030583

Wheeler, V. M., Kim, J., Daligault, T., Rosales, B. A., Engtrakul, C., Tenent, R. C., & Wheeler, L. M. (2022). Photovoltaic windows cut energy use and CO2 emissions by 40% in highly glazed buildings. *One Earth*, *5*(11), 1271–1285. https://doi.org/10.5281/zenodo.7243452

Widartha, V. P., Ra, I., Lee, S.-Y., & Kim, C.-S. (2024). Advancing smart lighting: A developmental approach to energy efficiency through brightness adjustment strategies. *Journal of Low Power Electronics and Applications, 14*(1), 6. https://doi.org/10.3390/jlpea14010006

Wolniak, R., & Stecuła, K. (2024). Artificial intelligence in smart cities—Applications, barriers, and future directions: A review. *Smart Cities*, *7*(3), 1346–1389. https://doi.org/10.3390/smartcities7030057

Worrakittimalee, T., Pienwisetkaew, T., & Naruetharadhol, P. (2024). The role of smart governance in ensuring the success of smart cities: A case of Thailand. *Cogent Social Sciences*, *10*(1), 2388827. https://doi.org/10.1080/23311886.2024.2388827

Yao, C. Z., Azli, M. N. A. N., Hariri, A., Damanhuri, A. A. M., & Mustafa, M. S. S. (2023). Preliminary study on student's performance and thermal comfort in classroom. *Journal of Advanced Research in Fluid Mechanics and Thermal Sciences, 101*(1), 59–72. https://doi.org/10.37934/arfmts.101.1.5972

Yin, J., & Song, H. (2023). Does the perception of smart governance enhance commercial investments? Evidence from Beijing, Shanghai, Guangzhou, and Hangzhou. *Heliyon*, *9*(8), e19024. https://doi.org/10.1016/j.heliyon.2023.e19024

Zhang, Q., Iqbal, S., & Shahzad, F. (2024). Role of environmental, social, and governance (ESG) investment and natural capital stocks in achieving net-zero carbon emission. *Journal of Cleaner Production*, *478*, 143919. https://doi.org/10.1016/j.jclepro.2024.143919

Zhao, J., Xie, X., Liu, R., Sun, Y., Wu, M., & Gu, J. (2018). Water and energy saving potential by adopting pressure-reducing measures in high-rise buildings: A case analysis. *Building Services Engineering Research & Technology*, *39*(5), 505–517. https://doi.org/10.1177/0143624417751056

Zupic, I., & Čater, T. (2015). Bibliometric methods in management and organization. *Organizational Research Methods*, *18*(3), 429–472. https://doi.org/10.1177/1094428114562629