Black Sea Journal of Engineering and Science
doi: 10.34248/bsengineering.1603629

Open Access Journal
e-ISSN: 2619 – 8991

Research Article
Volume 8 - Issue 3: 757-774/ May 2025

TECHNOLOGICAL ADVANCES IN AEC: AI, MACHINE LEARNING, BIM, AND THE FUTURE OF SUSTAINABLE BUILDING DESIGN IN A POST-PANDEMIC WORLD

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Abstract: The Architecture, Engineering, and Construction (AEC) industry has experienced a profound transformation, accelerated by the COVID-19 pandemic, which underscored the need for digital solutions to enhance sustainability and resilience. Despite existing technological advancements, the pandemic revealed gaps in the widespread adoption of tools like Artificial Intelligence (AI), Machine Learning (ML), Building Information Modeling (BIM), Internet of Things (IoT), and Digital Twins (DT). This study addresses the critical question of how these technologies have reshaped building design, construction, and operation processes to meet sustainability goals in the post-pandemic era. A systematic literature review of 35 peer-reviewed studies published between 2019 and 2024 was conducted to analyze the impact of key digital technologies on sustainable building practices. The research employed a thematic analysis focusing on technological advancements, sustainability applications, challenges and barriers, and emerging trends such as smart cities, renewable energy integration, and circular economy principles. The findings reveal that technologies like AI and DTs play a pivotal role in enhancing energy efficiency, enabling predictive maintenance, and improving lifecycle resource management. However, barriers such as interoperability issues, high implementation costs, and data security concerns persist, hindering widespread adoption. The study emphasizes the growing trend toward data-driven sustainability and the need to address these challenges through collaborative frameworks and technological innovation. In conclusion, this research highlights the transformative potential of digital technologies in advancing sustainability and resilience within the AEC industry. By bridging the gap between technological innovation and sustainable development goals, this study provides actionable insights for overcoming existing barriers and fostering adaptive, energy-efficient, and environmentally responsible built environments in a post-pandemic world.

Keywords: Digital technologies, Sustainable building design, Post-pandemic AEC industry, Artificial intelligence, Building information modeling, Digital twins

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Received: December 18, 2024
Accepted: March 26, 2025
Published: May 15, 2025

Cite as: Şenel Solmaz A. 2025. Technological advances in AEC: AI, machine learning, BIM, and the future of sustainable building design in a post-pandemic world. BSJ Eng Sci, 8(3): 757-774.

1. Introduction

The COVID-19 pandemic triggered unprecedented challenges globally, profoundly impacting industries such as Architecture, Engineering, and Construction (AEC). Beyond its health implications, the pandemic caused widespread economic disruption, delaying projects, exacerbating material and labor shortages, and mandating stringent health precautions. These disruptions underscored the vulnerabilities of traditional AEC practices and accelerated the adoption of digital technologies to ensure business continuity, efficiency, and safety in a rapidly changing environment (Yap et. al., 2019; Wang et al., 2021; Elrefaey et. al., 2022).

Before the pandemic, technologies such as Artificial Intelligence (AI), Machine Learning (ML), Building Information Modeling (BIM), and Internet of Things (IoT)-enabled systems were gradually being integrated into AEC processes. However, the urgency for remote planning, virtual collaboration, and adaptive project management during the pandemic transformed these technologies from optional tools to essential solutions (Magahed et. al., 2022; Alizadehsalehi et. al., 2020). Emerging innovations like Digital Twins (DTs), Augmented/Virtual Reality (AR/VR), and blockchain further enhanced real-time decision-making, predictive maintenance, and resource efficiency, paving the way for smarter and more resilient built environments.

While these technologies have been widely discussed, their transformative role in achieving sustainability goals during and after the pandemic remains underexplored. According to Elrefael et al. (2022), pre-pandemic digital technology investments often fell short due to underutilization and inadequate integration strategies. The crisis has since emphasized the critical need for evaluating digital tool adoption to support sustainable, efficient, and resilient buildings.

This study aims to address this gap by examining how the post-pandemic acceleration of digital technologies—specifically AI, ML, BIM, IoT, and DTs—is shaping sustainable building design, construction, and operation across the building lifecycle. Using a systematic literature review of 35 peer-reviewed studies (2019–2024), the research identifies:

- The applications of these technologies in energy

efficiency, lifecycle optimization, and resource management,
- The barriers to widespread adoption, such as interoperability, implementation costs, and data security concerns, and
- The emerging trends driving sustainability, such as smart cities, renewable energy integration, and circular economy principles.

By addressing these aspects, this paper offers new insights into the convergence of digital transformation and sustainability imperatives, highlighting the critical role of technology in fostering adaptive, efficient, and resilient built environments. The study's findings contribute to filling a research gap by providing actionable strategies for leveraging digital innovations to meet post-pandemic challenges and long-term sustainability goals in the AEC industry.

2. Literature Review

The COVID-19 pandemic brought unprecedented challenges, profoundly affecting global societies and economies while exposing vulnerabilities in the built environment (Elavarasan and Pugazhendhi, 2020). In densely populated areas, the heightened risk of pathogen exposure highlighted the critical need for infection control measures that extend beyond healthcare facilities. Measures such as improved ventilation, quarantine, social distancing, and disinfection became essential to mitigating cross-infection risks, which not only impacted health but also contributed to psychological stress and economic instability (Morawska et. al., 2020; Magahed and Ghoneim, 2021; Amoatey et. al., 2020; Shakil et. al., 2020). This experience underscored the importance of creating resilient, adaptable, and health-focused spaces capable of addressing both immediate public health needs and long-term sustainability goals (Coraglia et. al., 2024).

The pandemic also accelerated discussions in academia and industry, focusing on well-being within built environments (Mouratidis et. al., 2022; Gurram et. al., 2022), the need for resilient urban systems (Banai, 2020), and the integration of pandemic readiness into building design (Cheshmehzangi, 2021). Research has emphasized that the disruption caused by COVID-19 offers a critical juncture to reassess how sustainability is approached in the built environment, specifically advocating for a paradigm shift toward resilience and occupant health as central to future urban design (Coraglia et. al., 2024). While these discussions generated valuable insights, long construction cycles and reliance on traditional design approaches limited the development of practical, evidence-based guidelines. This gap highlights the urgency of rethinking building practices to prioritize adaptability, resource efficiency, and occupant health in the post-pandemic era (Han et. al. 2022).

Digital transformation has become a powerful driver of change, fundamentally reshaping how industries approach sustainability (Megahed and Ghoneim, 2020). The Digital Revolution—spanning technologies such as AI, IoT, and automated decision-making systems—has enabled the AEC industry to adopt greener, more resource-efficient practices, enhancing energy efficiency and reducing environmental impacts across the building lifecycle (Nakicenovic et. at.,2019; Aniekan Akpan et. al., 2024). Among these, DTs have emerged as a transformative tool, offering capabilities such as real-time monitoring, predictive maintenance, and disaster management (Megahed and Hassan, 2022). The pandemic accelerated the need for smart building technologies that support adaptive energy management and efficient resource use, emphasizing energy-saving measures and building retrofitting as essential components of sustainable recovery (Gorina et. al., 2024). By integrating IoT and AI, DTs support data-driven decision-making and scenario simulations, enabling improved energy performance and optimized resource use while mitigating future disruptions (Martínez-Cuevas et. al., 2024). These innovations not only address immediate pandemic-related challenges but also contribute to the broader sustainability goals of creating urban environments that are resilient, adaptive, and aligned with long-term environmental priorities (Megahed and Hassan, 2022; Martínez-Cuevas et. al., 2024).

Moreover, the pandemic's impact on residential buildings has highlighted an urgent need to transform sustainability requirements for these spaces. Research suggests that COVID-19 experience is reshaping how we think about residential building sustainability, emphasizing the integration of health-oriented features and increased energy efficiency in design (Tokazhanov et. al., 2020). Additionally, the global crisis has prompted a re-evaluation of building energy consumption patterns, highlighting that post-pandemic energy demands differ significantly from pre-pandemic trends. As many offices transitioned to remote work, energy usage in residential buildings surged, indicating the need for more energy-efficient home environments (Jogunola et. al., 2022). The integration of digital tools has become a transformative force in advancing sustainable practices across the AEC industry. These technologies such as BIM, IoT, and DTs are revolutionizing design, construction, and operational processes by enabling energy modeling, real-time monitoring, and predictive maintenance. By harnessing these capabilities, the AEC industry can achieve significant reductions in energy consumption, minimize environmental footprints, and extend the lifecycle efficiency of buildings. Digital technologies not only streamline resource management but also empower stakeholders with data-driven insights to create resilient and adaptable structures. As the backbone of sustainable innovation in AEC, digitalization addresses the complex challenges of modern construction while setting new standards for environmental responsibility. The following section explores key technological advancements including AI, BIM, IoT, and other emerging tools and highlights their vital contributions to sustainable building design and operation.

2.1. Technological Advancements Supporting Sustainable Building Design

The integration of digital technologies such as AI, ML, DTs, and the IoT is significantly transforming sustainable building design. These technologies enhance efficiency, reduce environmental impacts, and enable optimized resource utilization by creating a seamless connection between the physical and digital realms. AI and ML contribute significantly to predictive maintenance, energy modeling, and the analysis of complex datasets, allowing for smarter decision-making and reduced waste. Meanwhile, IoT employs smart sensors and automated controls to dynamically adapt building systems to changing conditions, improving energy efficiency and occupant comfort (Adewale et. al., 2024; Zhou and Liu 2024). DTs act as comprehensive virtual representations of physical assets, offering capabilities such as real-time monitoring, lifecycle optimization, and advanced simulations. These tools play a pivotal role in enhancing energy performance, promoting renewable energy integration, and achieving net-zero carbon objectives by providing actionable insights to minimize carbon footprints. Moreover, DTs improve indoor environmental quality, ensuring healthier and more sustainable living and working conditions (Megahed and Hassan, 2022; Martínez-Cuevas et. al., 2024; Zhou and Liu 2024). BIM complements these advancements by streamlining workflows, minimizing material waste, and enabling lifecycle analyses for resource-efficient construction projects. When combined with IoT, BIM facilitates dynamic modeling and real-time decision-making, while AI-driven systems deliver advanced simulations for energy optimization and adaptive resource management. Collectively, these technologies support human-centered and environmentally sustainable building designs, paving the way for resilient urban environments (Adewale et. al., 2024; Zhou and Liu 2024).

Beyond their role in construction, these digital technologies are driving innovation in energy systems, particularly in smart cities. By incorporating big data analytics, blockchain for secure energy transactions, and IoT-enabled energy networks, they enable effective planning, control, and optimization of energy systems. These innovations support the transition to renewable energy sources and energy-efficient buildings, establishing a foundation for sustainable urban development. However, challenges such as high implementation costs, interoperability issues, and data security concerns continue to hinder their widespread adoption, highlighting the need for further research and collaboration (Zhou and Liu 2024). Recent studies underscore the transformative potential of digital technologies in advancing sustainable building practices and smart city development. For instance, Adewale et al. (2024) explored the application of AI, ML, DTs, and IoT to reduce carbon footprints, optimize energy efficiency, and minimize waste across the building lifecycle. Key findings emphasized the role of AI in predictive maintenance and design optimization, IoT for automating building system controls, and DTs for real-time monitoring and lifecycle management. However, these advancements are hindered by barriers such as high implementation costs, data security, and gaps in technical expertise. Building on these insights, Bibri et al., (2024) highlighted the integration of AI, ML, and DTs into sustainable building design and smart city frameworks. This study showcased the synergy between AI and IoT for dynamic, data-driven management systems, enabling enhanced energy efficiency, reduced operational costs, and improved occupant comfort. To address interoperability and data security challenges, the authors recommended standardized frameworks and advanced algorithms to improve system scalability and reliability. Oulefki et al. (2024) further examined AI-driven advancements within DTs to optimize building operations and enhance sustainability in smart buildings. Their research focused on predictive maintenance, anomaly detection, and real-time optimization while emphasizing the integration of renewable energy sources. Promising future directions included leveraging generative AI for scenario modeling and addressing scalability challenges with quantum computing. Despite these innovations, issues like data privacy, standardization, and fault detection systems remain unresolved. In a broader exploration, Ferdaus et al. (2024) analyzed the role of AI, ML, DTs, IoT, robotics, and blockchain in driving the energy sector toward net-zero emissions. Their research identified applications such as AI and ML for energy optimization, DTs for real-time system management, and IoT for intelligent energy controls. Ethical considerations, including transparency and security, were emphasized as critical for responsible implementation. However, gaps in standardization and scalability were noted as key areas for interdisciplinary collaboration. Similarly, Arsecularatne et al. (2024) investigated the transformative impact of DTs, AI, ML, and IoT on energy efficiency, sustainability, and operational performance in smart buildings. This study highlighted the integration of these advanced technologies with BIM and Industry 4.0 concepts to tackle challenges in the AEC. Renganayagalu et al. (2024) focused on the integration of digital technologies within the framework of sustainable building design. Their research demonstrated the role of DTs, AI, ML, and IoT in optimizing energy performance and promoting sustainability across building systems, reinforcing the importance of technology in achieving long-term environmental goals.

The transformative impact of digital technologies on sustainable building design is evident through their diverse applications in energy management, lifecycle optimization, and operational efficiency. Each of these technologies—AI, ML, BIM, IoT, and DTs—offers distinct contributions, addressing unique challenges while complementing one another in fostering resilient and environmentally conscious building practices. By enabling predictive analytics, smart automation, and data-driven decision-making, these advancements align with the AEC industry's goals of reducing carbon footprints, enhancing resource efficiency, and creating adaptive structures. The following subsections delve into the key technological advancements that are redefining sustainable building design, emphasizing their unique roles, practical applications, and potential to drive the transition toward a more sustainable and resilient built environment.

2.2 Implementation of Digital Technologies Beyond the Pandemic

The COVID-19 pandemic accelerated the adoption of digital sustainability practices within the AEC industry, emphasizing resilience, remote capabilities, and comprehensive sustainability goals. Technologies such as IoT, BIM, digital twins, robotics, and AI-driven analytics were rapidly integrated to ensure operational continuity and sustainability. Technologies such as IoT, BIM, digital twins, and robotics have been increasingly integrated into building processes to ensure operational continuity and sustainability goals during and after the pandemic (Royan 2021). BIM evolved significantly from visualization to a critical tool for sustainability and circular economy, digitally documenting building components to create resource banks for material reuse, thus reducing reliance on scarce resources. According to Royan (2021), enhanced digital solutions are significantly driving CO_2 mitigation, climate adaptation, and digital-driven circular economy approaches, emphasizing resource-efficient reuse from the design phase.

The study by Parracho et al. (2025) highlights the significant post-pandemic shift toward modular and prefabricated construction, enabled by integrating BIM, DTs, IoT, and AI. These digitally-driven methods optimize carbon footprints, operational energy use, and material circularity. Post-pandemic digital transformation in the buildings has significantly enhanced sustainability and efficiency, with digital technologies such as AI, BIM, IoT, and smart meters enabling up to 30–50% improvement in building energy intensity by 2040. This adoption has primarily been driven by the need for improved indoor environmental quality, energy management, and operational resilience (Asif et. al. 2024). Furthermore, advanced AI-powered energy modeling and life cycle assessment (LCA) tools support the industry's movement towards off-grid, smart, and climate-responsive modular buildings.

The COVID-19 pandemic accelerated the adoption of digital technologies like BIM, remote collaboration tools, and advanced resource management systems in the construction industry. These technologies effectively mitigated disruptions caused by workforce shortages, logistical constraints, and material unavailability, reinforcing their essential role in enhancing project resilience and performance during crises (Pamidimukkala et al. 2025).

Piras et al. (2024) forecast that by 2025, DT-enabled smart building solutions will become prevalent, emphasizing real-time monitoring, automation, and predictive analytics. Yang et. al. (2022) further underline the importance of VR-enhanced training and AI-powered simulations to improve workforce efficiency and sustainability outcomes in modular construction. Pham et al. (2025) indicate that a significant post-pandemic transformation has been the integration of BIM with immersive technologies like VR and AR. These immersive solutions support collaborative design, interactive safety training, remote project management, and AI-driven hazard simulations, significantly addressing pandemic-induced constraints.

Moreover, the COVID-19 pandemic acted as a catalyst for digital transformation within construction tendering processes, significantly promoting electronic tendering (E-Tendering). However, the widespread adoption of this technology faced considerable barriers such as inadequate ICT infrastructure, data security concerns, high implementation costs, and resistance to change, highlighting the necessity for strategic interventions to overcome these challenges (Inusah et al., 2025). Integrated E-Tendering platforms leveraging BIM, AI, and DTs enhance decision-making, reduce paperwork, and increase transparency, though barriers such as cybersecurity risks, interoperability issues, resistance to AI-driven decision-making, and high investment costs persist. The construction industry's response to COVID-19 has underscored the critical role of digital and strategic resilience. The pandemic revealed significant vulnerabilities in traditional construction processes, prompting widespread adoption of digital technologies for project management, remote collaboration, and supply chain integration to mitigate disruptions and maintain operational continuity (Selcuk, 2025).

Chen et al. (2024) identify a key shift to fully integrated AI-DT ecosystems, making smart building management, predictive maintenance, and climate-responsive automation standard in energy-efficient construction. They also emphasize the necessity for policy-driven incentives to support digital adoption, particularly among SMEs. Emerging trends include AI and DT-driven monitoring, blockchain-based procurement, and AI-powered robotics and collaboration platforms, though cybersecurity risks, AI governance challenges, and the need for standardized frameworks remain.

Emerging digital ecosystems such as the Metaverse have shown potential to significantly transform the post-pandemic AEC by enhancing design simulation, stakeholder collaboration, and real-time performance assessment, particularly in the context of net-zero buildings. However, technological, infrastructural, and skill-based barriers continue to limit their broader adoption, necessitating strategic interventions from industry professionals and policymakers (Oguntona and Akinradewo 2025).

Despite significant benefits, digital technologies in the AEC raise critical concerns that require attention. Digital infrastructures, such as data centers and networks supporting AI, IoT, and DTs, entail considerable energy use, potentially exacerbating the carbon footprint rather than mitigating it. Additionally, ethical challenges, notably around data privacy, transparency, and ownership, become increasingly significant as reliance on automated decision-making grows. There is a critical need for stringent governance frameworks to ensure ethical AI practices. Moreover, excessive reliance on digital technologies might foster a risk of digital addiction, diminishing direct human interaction and potentially eroding traditional skills within the workforce, suggesting a need for balanced integration strategies that preserve essential human competencies and interactions.

A strategic approach toward post-pandemic AEC involves not only immediate technological adoption but also future-proofing buildings. As Wang et al. (2021) indicate, the extended construction cycle demands designing adaptable building systems that accommodate evolving technologies. Dynamic AI-driven, IoT-connected solutions are essential for enhancing building performance continuously and efficiently. Overall, the pandemic has been pivotal in advancing digitalization, placing digital technologies at the core of sustainability, resilience, and long-term adaptability in the AEC.

2.3. Artificial Intelligence and Machine Learning in AEC

The evolution of AI in the AEC industry has been extensively analyzed, with Darko et al. (2020) offering a scientometric review that traces historical and emerging research trends. Their study highlights the significant growth of AI research within the AEC industry over time, underscoring its increasing importance as AI, in combination with the IoT, enhances the industry's capacity to process complex, heterogeneous data. The authors use advanced techniques like co-citation and co-authorship analysis to map out the development of AI in the industry, offering valuable insights for future applications, especially in the integration of AI with other emerging technologies such as BIM and smart construction tools. Their research is particularly valuable for understanding how AI can shape future developments in smart building technologies, providing a solid foundation for further research in AI-powered sustainable building solutions.

Building on the broader role of AI, De Las Heras et al. (2020) delve into the integration of ML techniques, particularly in the context of smart cities, where urban growth and the COVID-19 pandemic have introduced new challenges. The study emphasizes the potential of ML to optimize sustainability by providing an inclusive framework for analyzing sustainability dimensions, applications, and tools. The authors propose the EARLY model as a future-oriented approach to enhance the sustainability and resilience of urban systems, supported by a case study in Andalusia. This contribution uniquely bridges the applicability of ML with Sustainable Development Goals (SDGs) in smart city contexts. Extending the discussion on AI and ML applications, Rathore et al. (2021) provide a comprehensive review of how these technologies, along with big data, contribute to the advancement of DTs. Their study focuses on both the challenges and opportunities associated with DT development, identifying key applications such as predictive maintenance and real-time data integration. By improving accuracy and predictive capabilities, AI and ML-driven DTs are positioned to enhance smart building performance significantly. The authors further emphasize the necessity of advanced machine learning algorithms to optimize these digital models, ensuring their functionality aligns with the evolving demands of sustainable and intelligent building systems.

Further reinforcing AI's transformative role in AEC, Rampini and Cecconi (2022) explore its applications in construction asset management, emphasizing both the challenges and opportunities in sustainability-driven innovation. Their review highlights how AI, when combined with emerging technologies such as DTs and Generative Adversarial Networks (GANs), can optimize asset management, reduce operational costs, and enhance building performance. By integrating AI with IoT, BIM, and other smart building technologies, they propose strategies for improving sustainability outcomes in construction and facility management. This research underscores the potential of AI-driven asset management to revolutionize the built environment, ensuring more efficient and resilient operations in the AEC.

Expanding on AI's role in shaping resilient urban environments, Strielkowski et al. (2022) examine how the COVID-19 pandemic underscored the need for adaptive, technology-driven urban management systems. Their study highlights the importance of integrating AI and IoT within smart cities to enhance resource management, public health strategies, and transportation systems, particularly during crises. The authors argue that the pandemic served as a catalyst for accelerating urban transformation, making cities more intelligent and resilient against future disruptions. In this context, they emphasize the potential of AI-driven governance models to improve real-time decision-making, providing a pathway for more sustainable and responsive urban development in the post-pandemic era.

As cities embrace AI-driven governance models to enhance urban resilience, the focus also shifts toward optimizing indoor environments through advanced digital technologies. Karatzas et al. (2024) present a comprehensive text-analytic framework that integrates DTs, ML, and AI to improve indoor building environmental performance. By leveraging AI and ML algorithms, the study processes large sets of environmental data to enhance energy efficiency, thermal comfort, and air quality in real-time. This integration is particularly valuable for exploring how AI and ML, in synergy with DTs, can enable adaptive, occupant-focused strategies for sustainable building management. The findings contribute to the broader discourse on leveraging advanced technologies for smart and sustainable construction.

As digital technologies continue to enhance building performance, their integration with advanced learning techniques further refines energy optimization strategies. Villano et al. (2024) provides an extensive review of machine and deep learning techniques applied to building energy simulation, optimization, and management. A key contribution is its emphasis on the role of hybrid models that combine traditional simulation techniques with machine learning for improved accuracy in energy performance prediction. The authors highlight the increasing relevance of reinforcement learning and neural networks for dynamic energy management systems, paving the way for automated optimization in building operations. They also identify future directions, including the integration of real-time data from IoT devices into AI frameworks to enable adaptive and predictive energy systems.

2.4. BIM and Integrated Systems

As AI and machine learning continue to shape energy-efficient and adaptive building management, another pivotal technology, BIM, has also experienced accelerated adoption, particularly in response to global disruptions. Wang et al. (2021) examine how the COVID-19 pandemic disrupted traditional workflows and significantly influenced BIM adoption in China's AEC industry. Their study applies event system theory (EST) and innovation diffusion theory (IDT) to highlight the role of external shocks in reshaping technology adoption strategies. A key contribution of their research is the exploration of how crisis-induced cognitive shifts among AEC stakeholders have driven BIM implementation, ultimately enhancing resilience and efficiency across the industry.

While the pandemic served as a catalyst for BIM adoption in the AEC, its impact extended beyond design and modeling to broader digital technology integration in construction workflows. Elrefaey et al. (2022) provides valuable insights into how the COVID-19 pandemic accelerated the adoption of digital technologies in construction, specifically in the UAE. The authors highlight the significant role of technologies such as drones, RFID, and 3D laser scanning in improving data acquisition, project management, and communication during the pandemic. These tools helped mitigate social distancing challenges and improved productivity by reducing survey time and enhancing safety on construction sites. The paper also emphasizes the barriers to wider digital technology adoption in construction, including economic and technical constraints. It suggests that future efforts should focus on overcoming these challenges by increasing investments in digital tools and training, which could lead to greater industry resilience and sustainability.

Similarly, as digital technologies continue to drive efficiency in construction, the integration of advanced management systems with BIM plays a crucial role in optimizing energy performance. Kozlovska et al. (2023) examine the synergy between Building Energy Management Systems (BEMS) and BIM, emphasizing their combined potential to enhance energy efficiency and overall building performance. Through real-world case studies, their study demonstrates how this integration improves energy use within buildings while addressing key challenges such as data uncertainties and software interoperability. In addition to streamlining energy management, the authors highlight BIM's essential role in optimizing industrial buildings for sustainable operations. By bridging the gap between energy management and digital modeling, this research underscores the importance of BIM-BEMS integration in fostering energy-efficient practices and contributing to the broader goal of sustainable construction.

In addition to enhancing energy efficiency in building management, the integration of BIM with emerging digital technologies extends its impact to industrial infrastructure. Badenko et al. (2024) introduce principles for sustainably integrating BIM and DT technologies in industrial settings, focusing on minimizing environmental impact, optimizing resource efficiency, and ensuring long-term resilience. Their study presents a framework to achieve these goals through lifecycle management, data interoperability, and stakeholder collaboration, proposing key solutions for the challenges faced in "Factories of the Future." This work lays the groundwork for future research and real-world applications in sustainable industrial operations.

2.5. IoT and Smart Building Systems in Sustainable Design

Similarly, as BIM and DT technologies continue to transform industrial infrastructure, their integration with the IoT is increasingly shaping the future of smart building systems. The study by Tang et al. (2019) provides an in-depth review of the integration of BIM and IoT, focusing on their synergy to enhance building performance, optimize energy use, and improve occupant comfort. They discuss current technological challenges and benefits, with a particular emphasis on the role of IoT devices like sensors in providing real-time data. The paper highlights future trends towards seamless integration, focusing on data interoperability and real-time analytics, which will be essential for advancing smart building systems and contributing to smart city development.

Expanding on the challenges associated with smart city development, Wang et al. (2021) investigate the adoption challenges of IoT and AI technologies in smart cities, focusing on China. Their research identifies key obstacles such as technical complexity, data security, and the shortage of skilled professionals, and introduce a cause-and-effect model using the DEMATEL method to understand the interconnections between these challenges. The study advocates for coordinated efforts by policymakers, industry leaders, and researchers to overcome these obstacles, particularly by strengthening infrastructure and human capital to enable successful smart city development.

Building on the role of IoT in enhancing urban resilience, Xie et al. (2022) examine smart building technologies aimed at addressing challenges introduced by the COVID-19 pandemic. Their study makes a particularly valuable contribution by exploring innovative ventilation systems and air-quality management solutions designed to mitigate virus transmission in indoor environments. Emphasizing the integration of IoT-enabled sensors and smart systems, the research highlights their effectiveness in monitoring and improving indoor environmental quality (IEQ). In addition, the authors propose strategies for embedding these technologies into future building designs, ensuring resilience and health-focused construction that can adapt to similar public health crises. In addition to improving indoor environmental quality, the integration of advanced technologies is also transforming energy management in buildings. Naeem et. al. (2024) highlights how Industry 4.0 technologies like AI and IoT can optimize renewable energy systems through enhanced performance and predictive maintenance. It suggests that deeper integration of these technologies into building systems could further boost energy efficiency and sustainability. Similarly, the study by Asif et al. (2024) highlights the role of digital technologies like BIM, IoT, and DTs in improving building performance and sustainability. It emphasizes challenges such as data privacy, integration difficulties, and high initial costs, while proposing the expansion of these technologies to reach net-zero energy goals through advanced analytics and automation.

2.6. Digital Twins: A Nexus of Virtual and Physical Systems

As digital technologies continue to drive innovation in building performance and sustainability, DTs are emerging as a transformative solution that bridges the gap between virtual modeling and real-world applications. Zhang et al. (2021) review the role of DTs in enhancing sustainability within positive energy districts. It highlights how DTs integrate with simulation tools to optimize building performance, manage energy efficiency, and enable sustainable urban development. The authors emphasize the potential of twins to accelerate the transition towards positive energy districts by offering real-time insights into energy usage patterns. They suggest that future work should explore twins' scalability and adaptability to varying urban contexts, contributing to smarter and more sustainable cities. Similarly, Zhang et al. (2024) extend this discussion by exploring how DT technologies can enhance sustainability in the construction industry through their integration with BIM, IoT, AI, and other advanced technologies. Their study underscores the importance of DTs in optimizing resource usage and minimizing environmental impacts throughout both construction and operation phases. However, realizing the full potential of twins requires overcoming challenges related to data integration and scalability. Addressing these limitations could pave the way for more effective and widespread adoption of DTs, reinforcing their role as a cornerstone of sustainable construction practices. In addition to their role in resource optimization, DTs are also transforming how buildings manage energy efficiency and occupant comfort. The research conducted by Arowoiya et al. (2024) explores the application of DT technology in improving thermal comfort and energy performance in buildings. It highlights the evolving role of DTs in optimizing building performance by providing real-time monitoring and predictive analytics, particularly in the context of energy use and indoor environmental quality. A unique contribution of this work lies in its thorough review of how DTs can be integrated with thermal comfort systems and energy management frameworks, enabling adaptive strategies for sustainability. The paper also discusses future directions, emphasizing the need for further research into dynamic, occupant-centric solutions that can adapt to changing building conditions and user preferences. Expanding on the potential of twins in sustainable construction, the study by Zahedi et al. (2024) examines how they contribute to optimizing building performance, improving energy efficiency, and enabling real-time monitoring of environmental conditions. Their research focuses on the integration of twins with other emerging technologies like AI and IoT to enhance energy efficiency and operational sustainability in buildings. Furthermore, the study identifies gaps in current research and calls for more attention to the development of scalable DT models that could provide more reliable predictive analytics for building lifecycle management. This work provides valuable insights into the future direction of DT in sustainable construction, especially regarding the need for continuous innovation and integration of smart technologies to meet sustainability goals.

Similarly, Yoon et al. (2024) explore how the integration of twin technology with BIM enhances building operations and maintenance. It highlights the potential of using real-time data for predictive analytics and seamless interactions between physical and digital assets, improving energy efficiency, sustainability, and operational performance. The paper suggests future directions that focus on enhancing real-time modeling capabilities and expanding the integration of these technologies for dynamic building management. Extending the application of DTs beyond individual buildings, García-Aranda et al. (2024) investigate their role in urban sustainability, using a university campus in Madrid as a case study. Their research demonstrates how twins can simulate and optimize urban planning strategies, focusing on energy management, waste reduction, and resource efficiency. The study uniquely emphasizes the role of DTs in enhancing decision-making for sustainable urban development. Future research should integrate social and behavioral factors into DTs to promote more participatory and inclusive urban planning. In addition to their role in sustainable urban planning, DTs are also transforming smart city management through their integration with big data and real-time analytics. Lv et. al. (2022) explores the integration of DTs and BIM with big data to optimize smart city management, particularly during the COVID-19 pandemic. Its unique contribution lies in showing how these technologies can enhance urban management by enabling real-time data exchange and predictive analytics to increase the adaptability and resilience of infrastructure during crises. The authors highlight the importance of further integrating advanced data analytics with DT and BIM to improve the sustainability and efficiency of smart city systems in the future. Similarly, Yang et al. (2022) investigate the potential of twin technologies in enhancing energy efficiency and sustainability in green buildings. The study highlights how DTs can simulate and monitor building systems in real-time, enabling dynamic adjustments to optimize resource use and maintain occupant comfort. A unique contribution of this study is its emphasis on integrating AI and data analytics into DT frameworks to predict system behaviors and facilitate decision-making. The paper also underscores future directions, including the need for standardized frameworks and increased focus on cybersecurity to fully realize the potential of DTs in intelligent building management systems.

Building on the integration of digital technologies in the built environment, the study by Sepasgozar et al. (2023) explores the convergence of BIM and twin technologies, emphasizing their transformative impact on the construction industry. Their study discusses how these technologies can enhance automation, integration, and sustainability in construction processes. The authors also provide a roadmap for implementation, pointing to their significant role in shaping future digital construction practices.

Expanding on the role of DTs in optimizing built environments, Tahmasebinia et al. (2023) examine their integration in building energy management, emphasizing capabilities in real-time monitoring, energy consumption prediction, and overall efficiency enhancement. A key focus of their study is the combination of DT with machine learning techniques, which significantly improves predictive accuracy and optimizes building performance. Looking ahead, the authors suggest that further advancements in these integrations could drive even greater energy efficiency and support sustainable development goals, particularly in the context of intelligent energy management systems.

2.7. Emerging Technologies and Specialized Applications (e.g. AR/VR, Robotics, Blockchain, 3D Printing)

Emerging technologies in AEC are redefining sustainable construction by integrating innovative solutions into complex building systems. AR and VR facilitate enhanced visualization and real-time collaboration, improving design processes and project efficiency. Robotics and drones are transforming site management by increasing precision, safety, and speed in construction operations (Elrefaey et. al., 2022). Similarly, blockchain technology ensures security and transparency in managing construction supply chains, while addressing the digital vulnerabilities through advanced cybersecurity measures (Naeem et. al., 2024).

Zhou and Liu (2024) highlighted several research gaps regarding digital technologies and energy efficiency in buildings and smart cities from a sustainability perspective. These include a lack of comprehensive reviews on energy digitalization technologies for high-efficiency, low-carbon building energy systems and unclear roles of tools like IoT, blockchain, and DTs in integrated multi-energy systems. Additionally, distributed energy systems face unaddressed challenges in system configurations, multi-agent energy management, and energy flexibility for managing spatial and temporal mismatches in renewable resources. The resilience of energy systems to both frequent low-impact events (e.g., climate change) and rare high-impact events (e.g., extreme weather, regional conflicts) also requires further exploration with digital technologies.

Specialized applications, such as Generative Adversarial Networks (GANs), neural networks, and computer vision, are offering novel methods for analyzing architectural data, leading to refined modeling and simulation practices (Rampini and Cecconi, 2022). Additionally, 3D printing accelerates prototyping and facilitates on-demand construction, while RFID technology streamlines asset tracking and logistics (Elrefaey et. al., 2022). These tools not only optimize workflows but also reduce waste, contributing to sustainability goals.

Collectively, these cutting-edge innovations highlight the transformative potential of technology in achieving net-zero and sustainable construction objectives. However, they also underscore the importance of overcoming challenges such as system integration, cost barriers, and workforce development. As research continues to advance, multidisciplinary approaches will be key to unlocking the full potential of these emerging technologies in the built environment.

3. Materials and Methods

This study utilized a systematic literature analysis to investigate the role of digital technologies in advancing sustainable building design in the post-pandemic era. The literature review followed a structured selection process, beginning with an extensive database search that initially retrieved thousands of articles. To ensure relevance and quality, a rigorous screening process was applied based on predefined inclusion criteria, prioritizing peer-reviewed studies published between 2019 and 2024. After careful evaluation, 35 studies focusing on digital technologies and sustainability in the

AEC were selected, with particular emphasis on the impact of post-pandemic developments. A comprehensive literature search was conducted using Google Scholar, focusing on peer-reviewed publications from 2019 to 2024.

3.1. Literature Search and Selection Process

To ensure relevancy, specific keywords were used, including:

- "digital technologies in sustainable design",
- "post-COVID sustainability practices in AEC", and
- "impact of COVID-19 on AEC".

The search yielded a total of 35 peer-reviewed papers that were selected based on their contributions to the integration of advanced technologies such as AI, ML, BIM, and DTs in promoting sustainability in building design and construction. The inclusion criteria focused on peer-reviewed studies published between 2019 and 2024 that explored the role of digital technologies (AI, ML, BIM, IoT, and DTs) in advancing sustainability within the AEC industry. Non-peer-reviewed articles, studies unrelated to AEC, and those published before 2019 were excluded to maintain the relevance and rigor of the review.

The findings of this study provide valuable insights into how the COVID-19 pandemic accelerated digital transformation in the AEC industry and highlight the critical role of advanced technologies in achieving sustainability goals. By analyzing key applications, barriers, and future trends, this research contributes to the development of actionable strategies for integrating digital tools to address resource efficiency, energy optimization, and resilience in building systems.

3.2. Statistical Analysis

The selected papers were analyzed using a thematic analysis methodology involving a structured, qualitative approach to identify, analyze, and report patterns within the data. Initially, all selected literature underwent a thorough review to ensure familiarity with the content, followed by systematic coding to highlight significant concepts related to digital technologies, sustainability practices, challenges, and emerging trends within the AEC industry post-pandemic. Themes were iteratively developed through reviewing and grouping related codes, ensuring comprehensive coverage of critical topics.

The evaluation criteria employed for selecting the final 35 peer-reviewed articles included their explicit relevance to key digital technologies (AI, ML, BIM, IoT, DTs), their clear demonstration of implications for sustainable practices within building design and construction, peer-reviewed publication status, and publication timeframe between 2019 and 2024. Studies not meeting these predefined criteria were excluded to maintain methodological rigor and relevance.

The thematic analysis specifically focused on the following key aspects:

- Technological Advancements: Examination of digital tools such as AI, IoT, and DTs for optimizing energy efficiency, predictive maintenance, and real-time performance monitoring.
- Sustainability Applications: Identification of technologies that address resource efficiency, energy optimization, and lifecycle sustainability.
- Challenges and Barriers: Analysis of constraints such as interoperability issues, high implementation costs, and data privacy concerns that hinder broader adoption.
- Emerging Research Trends: Highlighting focus areas such as smart cities, renewable energy integration, and the use of advanced data analytics.

To summarize the findings, a table was compiled to organize the selected studies, their contributions, and relevant keywords. Additionally, a word cloud was generated to visualize the dominant themes and technologies identified during the analysis.

3.3. Visual Data Representation

To visualize the key trends identified from the literature analysis, Figures 2 through 5 illustrate the relationships between technological advancements and sustainability challenges, and practical applications in the AEC industry. This approach provided a clear overview of the emerging trends shaping sustainable building practices in a post-pandemic context.

4. Results

This section presents the results derived from the thematic analysis of the selected literature. The qualitative data collection and analysis methods utilized are detailed comprehensively in section 3. Materials and Methods. The subsequent sections specifically focus on interpreting and discussing the key research trends, technological advancements, sustainability applications, challenges, and barriers identified through this analysis, rather than revisiting methodological details.

The analysis highlighted key findings across several areas: technological advancements, sustainability applications, challenges and barriers, and emerging research directions. Technologies such as AI, IoT, and DTs were found to play crucial roles in optimizing energy efficiency, monitoring building performance in real-time, and enabling predictive maintenance. Challenges such as interoperability, high costs, and data privacy were also identified as significant barriers to the broader adoption of these technologies in the AEC. The research further revealed a shift in the industry towards a more data-driven approach to sustainability, with increasing emphasis on smart cities, renewable energy integration, and the use of data analytics for optimizing building performance. To summarize these findings, a Table 1 was compiled listing the 35 selected studies, their contributions, and associated keywords. Table 1 provides an organized overview of the technological trends and research themes emerging in sustainable building design post-COVID. The subsequent sections will explore these trends in more detail, shedding light on the key drivers shaping the future of sustainable building practices in the AEC industry.

Table 1. Overview of key technologies, applications, and future directions for sustainability in the AEC industry

Author(s) and Year	Technologies Utilized	Purpose and Objectives of Key Technologies	Applications for Sustainability	Challenges and Barriers	Research Keywords	Key Findings and Contributions	Future Research Directions
Tang et al. (2019)	BIM, IoT	To explore BIM and IoT integration for improving construction, operation, and facility management	Real-time monitoring, energy management, disaster response	Interoperability, lack of integration standards, sensor reliability	BIM, IoT, facility management, construction monitoring, sustainability	Identified integration methods for BIM and IoT and proposed applications in health and safety, resource monitoring	Research on service-oriented architecture (SOA) patterns, cloud computing, and interoperability for BIM-IoT systems
Darko et al. (2020)	AI (Genetic Algorithms, Neural Networks, ML)	To evaluate the role of AI in optimizing processes and decision-making in the AEC industry using scientometric analysis	Energy optimization, project management, lifecycle efficiency	Limited cross-discipline collaboration, data integration issues	AI, Genetic Algorithms, Neural Networks, Machine Learning, AEC	Highlights widespread use of Genetic Algorithms and Neural Networks for optimization and decision-making in AEC applications	Focus on integrating AI with robotics, life cycle assessment, thermal comfort, and energy efficiency in the AEC industry
De Las Heras et al. (2020)	ML	to enhance the efficiency of urban services, minimize environmental impacts, and foster sustainability in smart city operations.	optimizing energy use in buildings, improving air quality monitoring, and deploying intelligent transportation systems for sustainability.	limited data availability, integrating diverse urban subsystems, and addressing ethical concerns related to privacy and data security.	ML, Smart Cities, Sustainability, Urban Monitoring, Energy Optimization, Air Quality Monitoring, Intelligent Transportation Systems, Data Privacy	Demonstrates that machine learning provides adaptive and predictive tools, enabling smarter and more sustainable urban services and infrastructure.	Recommends refining ML algorithms for better energy optimization, scaling applications to mid-sized cities, and integrating blockchain with IoT for secure ecosystems.
Rathore et al. (2021)	AI, ML, Big Data, IoT, DTs	To systematically review the integration of AI-ML and Big Data with DTs to optimize industrial processes and enhance decision-making	Smart manufacturing, resource efficiency, predictive maintenance, fault detection	Interoperability, data privacy, lack of standards	DTs, AI, ML, Big Data, IoT, Industry 4.0	Proposed a big data-driven, AI-enriched reference architecture for creating DT-enabled systems; identified tools and frameworks for DT creation	Addressing data standardization challenges, developing multi-domain DT frameworks, and exploring advanced AI-ML algorithms for real-time optimization
Wang et al. (2021)	BIM	To explore the influence of the COVID-19 pandemic on BIM adoption intention using event system theory and innovation diffusion theory	Enhanced collaboration, emergency construction (e.g., hospitals), reduced rework, real-time monitoring	High complexity, interoperability issues, low adoption rates in developing countries	BIM, COVID-19, adoption intention, event criticality, innovation diffusion	Demonstrated that perceived event criticality and technical features (compatibility, relative advantage) indirectly influence BIM adoption intention	Promoting BIM adoption through government incentives, cross-cultural research, and stakeholder-specific adoption studies
Wang et al. (2021)	IoT, AI	To analyze and address challenges in adopting IoT and AI for sustainable smart cities in China	Smart transportation, energy distribution, waste management, public health optimization	Lack of infrastructure, insufficient funds, cybersecurity risks, lack of trust in AI and IoT, skilled professional shortages	IoT, AI, smart cities, sustainability, adoption challenges, DEMATEL	Established cause-effect relationships among ten identified adoption challenges; proposed strategies for overcoming barriers to enhance AI and IoT implementation in urban management	Addressing data security, enhancing trust in AI and IoT technologies, promoting scalable frameworks for smart city applications
Zhang et al. (2021)	DTs, IoT, AI, BIM	To review the role of DTs in Positive Energy Districts (PEDs), including simulation tools and applications	Energy optimization, circular economy, climate neutrality	Data analysis, semantic interoperability, business model challenges, data security and management	DTs, PEDs, energy optimization, AI	Identified digital twin tiers: (1) enhanced BIM, (2) semantic platforms, (3) AI-enabled agents; proposed integration of multi-tier tools for PED optimization	Focus on advanced AI/ML methods for predictive analytics and holistic sustainability strategies in PEDs
Rampini and Cecconi (2022)	AI, DTs GANs, ML, Neural Networks, Computer Vision	To analyze the current applications of AI in construction asset management, identify research gaps, and explore emerging trends for future developments	Energy management and optimization, condition assessment for predictive maintenance, risk management, lifecycle cost reduction	High implementation costs, limited interoperability, lack of structured datasets for AI training	Asset Management, AI, Neural Networks, Machine Learning, Computer Vision	dentified AI applications in energy, risk, and lifecycle management; highlighted trends like GANs for data augmentation, DTs for real-time monitoring, and bibliometric analysis of research gaps	Developing frameworks for data standardization and interoperability; exploring hybrid AI models for decision-making; integrating DTs with AI for lifecycle management
Strielkowski et al. (2022)	AI, IoT, Big Data, Blockchain	To assess how smart city technologies and governance principles contributed to sustainable urban management during and post-COVID-19	Urban resilience, energy management, intelligent transport systems	High costs, interoperability, need for data privacy	Smart cities, sustainability, urban mobility, AI, IoT, post-COVID-19	Highlighted integration of ICT and AI in smart city resilience strategies; proposed frameworks for pandemic-resilient urban planning and mobility	Emphasized importance of advancing privacy-preserving AI and expanding international collaboration for more robust, scalable smart city solutions
Elrefaey et al. (2022)	BIM, Drones, RFID, Laser Scanning, Cloud Computing	To evaluate the impact of COVID-19 on digital technology adoption in the UAE construction industry	Enhanced project success through data-driven decision-making and virtual collaboration	High initial costs, lack of training, data privacy concerns	BIM, Drones, RFID, Construction Productivity, COVID-19	Identified a significant increase in digital technology adoption during and after COVID-19, with smaller organizations accelerating investments	Broader adoption of data-driven virtual technologies, addressing training gaps, and improving interoperability
Megahed et al. (2022)	AI, BIM, IoT, DTs	To investigate the evolution of BIM into DTs for optimizing the AECO sector	Achieving Sustainable Development Goals (SDGs), enhancing cyber-physical integration	Technical, societal, and operational challenges	BIM, DTs, IoT, AI, sustainability, lifecycle optimization	Demonstrated the potential of DTs in planning, managing, predicting, and optimizing AECO projects to achieve SDGs	Proposes theoretical models to validate DTs frameworks and encourages future quantitative studies involving stakeholder perspectives
Xie et. al. (2022)	IoT, AI, automation technologies .	To enhance health, safety, and energy efficiency in buildings, with a specific focus on pandemic resilience through smart, adaptive systems.	Optimizing energy use, reducing operational costs, lowering carbon emissions, and improving indoor air quality through intelligent systems.	Cybersecurity risks, data privacy concerns, and high costs of deployment and maintenance.	Smart buildings, IoT, pandemic resilience, AI, energy optimization, adaptive technologies.	Demonstrates the pivotal role of smart systems (e.g., HVAC optimization, occupancy-focused controls) in pandemic preparedness and in ensuring sustainable building operations.	Enhancing system interoperability, advancing AI for predictive maintenance, and addressing ethical concerns related to data usage and privacy.
Lv et al. (2022)	DTs, BIM, Big Data, IoT, AI, Cloud Computing, ML, Bayesian Networks	To improve the management and construction of smart cities by integrating BIM and DTs with advanced data-processing technologies	Enhanced urban resource management, real-time monitoring for disaster response and public health, smart city infrastructure optimization	High complexity of big data integration, data uncertainty, lack of interoperability between systems	Smart cities, DTs, BIM, IoT, AI, Bayesian Networks, Big Data, urban management	Proposed a Bayesian Network Structural Learning (BNSL) algorithm for handling complex multi-dimensional urban data, integrated DTs and BIM for enhanced predictive analytics and management	Development of advanced algorithms for multi-source heterogeneous data fusion, application of semi-supervised and multimodal learning techniques for smart cities
Yang et. al. (2022)	DTs, data-driven simulation, monitoring	To enhance Intelligent Green Buildings (IGBs) by integrating DTs for real-time system management, efficiency, and optimization.	Resource optimization, energy savings, reduced environmental impact, and improved building system intelligence.	Limited integration frameworks for DTs, issues with data standardization, interoperability challenges, and high implementation costs.	DTs, Intelligent Green Buildings, sustainability, smart cities, predictive analytics.	DTs significantly enhance IGB functionality by bridging virtual and physical systems, providing insights for sustainable urban development.	Focus on integrating DTs with smart city technologies, advancing green design, and addressing socio-economic challenges.

Table 1. Overview of key technologies, applications, and future directions for sustainability in the AEC industry (continued)

Author(s) and Year	Technologies Utilized	Purpose and Objectives of Key Technologies	Applications for Sustainability	Challenges and Barriers	Research Keywords	Key Findings and Contributions	Future Research Directions
Kozlovska et al. (2023)	BEMS, BIM, DTs, IoT, AI, ML	To explore the synergy between BEMS and BIM for improving energy efficiency and overall building performance through integrated monitoring and control	Real-time energy usage monitoring, enhanced indoor environmental quality, lifecycle energy optimization	Lack of interoperability, limited data exchange standardization, high implementation costs	Building Energy Management Systems, BIM, Digital Twin, Energy Efficiency, Sustainability, Building Performance	Demonstrated BEMS-BIM integration reduces energy consumption and improves sustainability; highlighted Digital Twin applications in bridging physical-virtual system gaps	Standardized protocols for BEMS-BIM data exchange; expanded Digital Twin capabilities for predictive energy management; cost reduction strategies for system implementation
Sepasgozar et al. (2023)	BIM, DTs, IoT, AI, VR, AR, Cloud Computing, Industry 4.0	To identify and leverage disruptive and convergent technologies in construction	Circular economy principles for resource efficiency, energy optimization through digital workflows, remote operation and monitoring for construction	High implementation costs, resistance to change in construction, interoperability and standardization issues, data security and management challenges	BIM, DTs, IoT, VR, AR, sustainability, Industry 4.0, circular economy	Highlighted the importance of BIM and DT integration for lifecycle sustainability, proposed a framework for digital adoption aligned with Industry 4.0 principles, showcased immersive technologies for training and safety	Development of standards for integrating DTs with advanced manufacturing, exploration of AI-assisted immersive technologies, enhancing data interoperability and security across platforms
Tahmasebinia et al. (2023)	DTs, BIM, IoT, ML, Energy Simulation Tools	To explore the potential of DT technology in improving energy efficiency and achieving sustainability through real-time monitoring and optimization	Real-time energy monitoring, predictive maintenance, simulation of energy performance, carbon emissions reduction	High computational demands, interoperability issues, economic and policy-related barriers	Digital Twin, BIM, Machine Learning, Energy Efficiency, Carbon Emissions, Building Management Systems	Demonstrated how DTs improve operational efficiency and reduce carbon footprints, integrated real-time data from BIM and IoT systems, and optimized HVAC systems	Development of advanced ML algorithms for energy prediction, exploring policy frameworks, enhancing system interoperability
Adewale et al. (2024)	AI, ML, DTs, IoT	To optimize building performance and reduce environmental impacts through smart systems	Carbon footprint reduction, energy efficiency, waste minimization	High implementation costs, data security, skills gap	AI, ML, IoT, DTs, sustainability, building lifecycle	AI for predictive maintenance, IoT for system automation, DTs for real-time monitoring	Overcoming data privacy issues, improving scalability
Bibri et al. (2024)	AI, ML, DTs, IoT	Enhance sustainability in smart cities and buildings through data-driven technologies	Energy optimization, cost reduction, occupant comfort	Data security, standardization issues	AI, ML, IoT, smart cities, energy management	AI and IoT for dynamic management systems, DTs for building performance	Implementing advanced algorithms, standardized frameworks
Oulefki et al. (2024)	AI, DTs	Optimize building operations and enhance sustainability through AI-powered solutions	Predictive maintenance, renewable energy integration	Data privacy, standardization, scalability	AI, DTs, smart buildings, predictive maintenance	Use of AI for anomaly detection, generative AI for scenario modeling	Overcoming fault detection challenges, expanding AI integration
Ferdaus et al. (2024)	AI, ML, DTs, IoT, Robotics, Blockchain	Drive energy sector toward net-zero emissions through digital technologies	Optimization of energy systems, enhancing renewable adoption	Ethical issues, standardization gaps	AI, ML, IoT, blockchain, energy efficiency, sustainability	AI for energy optimization, DTs for real-time monitoring	Standardization, scalability, ethical considerations
Arsecularatne et al. (2024)	AI, ML, IoT, DTs, BIM, Industry 4.0	Improve energy efficiency, sustainability, and operational performance in buildings	Integration of renewable energy sources, resource efficiency	High costs of implementation	AI, IoT, BIM, energy efficiency, sustainability	Integration of DTs with BIM for optimized energy management	Addressing costs and scalability in smart building solutions
Renganayagalu et al. (2024)	AI, ML, IoT, DTs	Promote sustainability and optimize energy performance in buildings	Energy optimization, resource management	Data integration challenges	AI, ML, IoT, energy performance, building systems	Use of DTs for energy performance, AI for optimization	Research into generative AI and predictive analytics for building systems
Karatzas et al. (2024)	AI, ML, DTs	To propose a text analytic framework for exploring the integration of DTs and Machine Learning to optimize indoor environmental performance	Energy efficiency, occupant comfort, indoor air quality (IAQ)	Interoperability challenges, lack of autonomous optimization	DTs, AI, ML, indoor environment quality, energy efficiency, occupant comfort	Developed a clustering framework leveraging Digital Twin architecture and AI/ML for analyzing indoor environmental quality and energy efficiency	Expanding autonomous, real-time optimization for DTs and analyzing AI/ML applications in improving indoor air quality and occupant well-being
Villano et al. (2024)	ML, DL, ANNs, Decision Trees, SVM, Kriging, CNN, LSTM	To categorize and evaluate ML/DL techniques for predicting, optimizing, and managing building energy consumption	Energy design and retrofit optimization, renewable energy integration, fault detection, control of heating/cooling systems	High computational costs, need for large datasets, limited model interpretability	Machine Learning, Deep Learning, Artificial Neural Networks, Energy Efficiency, Fault Detection	Identified the most commonly used ML/DL models and their energy management applications; emphasized ANN advantages for predictive accuracy; discussed DL strengths for time-series data	Development of hybrid frameworks combining ML/DL for prediction and control; creation of large-scale datasets; exploration of explainable AI for model interpretability
Badenko et al. (2024)	BIM, DTs, Facility Management.	To develop a strategic framework for integrating BIM and DTs in industrial infrastructure to address sustainability challenges such as environmental impact reduction and resource optimization.	Lifecycle management, data interoperability, and greener industrial practices.	Limited stakeholder collaboration and the complexity of implementing digital workflows.	sustainable industry, building information modelling, Factory of the Future, industrial facilities, digital twin, facility management	Proposed principles for Factory of the Future models using BIM-DTs for enhanced operational sustainability.	Expanding DT applicability in industrial automation and refining multi-stakeholder frameworks
Naeem et al. (2024)	AI, IoT, Blockchain, DT, 3D Printing, Big Data Analytics, Robotics, Sensors, Cloud Computing, Cybersecurity	To explore the functions, applications, and challenges of Industry 4.0 digital technologies in renewable energy systems (RES).	Renewable energy optimization, energy production and consumption efficiency, predictive maintenance, cost-effectiveness, and resource management	High implementation costs, interoperability issues, cybersecurity risks, potential job displacement	AI, IoT, Blockchain, Industry 4.0, Renewable Energy, Digital Twin, Big Data, 3D Printing, Robotics, Cybersecurity	Highlighted the transformative role of Industry 4.0 technologies in enhancing efficiency, sustainability, and cost reduction in RES; practical examples include AI improving solar panel efficiency by 20% and reducing production costs by 50%.	Addressing interoperability challenges, cybersecurity frameworks, collaborative policies, and integrating advanced AI models for RES management

Table 1. Overview of key technologies, applications, and future directions for sustainability in the AEC industry (continued)

Author(s) and Year	Technologies Utilized	Purpose and Objectives of Key Technologies	Applications for Sustainability	Challenges and Barriers	Research Keywords	Key Findings and Contributions	Future Research Directions
Asif et al. (2024)	AI, BIM, IoT, DTs, Blockchain, Machine Learning, Smart Meters, Sensors, 3D Printing	To analyze the role of digitalization and 13 key digital technologies in enhancing building sustainability across the lifecycle.	Energy optimization, real-time monitoring, predictive maintenance, waste reduction, enhanced user comfort, carbon footprint reduction, renewable energy	High initial cost, lack of skilled workforce, privacy and security risks, low customer awareness, interoperability issues	AI, BIM, IoT, DTs, Sustainability, Energy Efficiency, Renewable Energy, Smart Meters, Climate Change	Demonstrated a 30–50% improvement in building energy intensity by 2040 through digital technologies; highlighted applications like sensors for real-time data, BIM for sustainability assessments	Development of cost-effective digital solutions, enhanced cybersecurity measures, and increased workforce training; exploration of integrated applications across building lifecycle stages
Zhang et al. (2024)	DTs, IoT, Data Fusion Techniques, AI.	To establish a conceptual framework for the implementation of DTs in reducing carbon emissions throughout the lifecycle of buildings.	Emission monitoring, optimization of construction processes, and real-time analytics for carbon reduction strategies.	Deployment costs, lack of interoperability standards, and limited stakeholder awareness.	DTs, sustainability, construction industry	Proposed proof-of-concept examples demonstrating DT's potential for transforming traditional construction practices into sustainable workflows.	Research into cost-effective implementations and enhancing AI-driven DT applications for resource efficiency
Arowoiya et al. (2024)	DT, AI, IoT, Sensors, ML (YOLOv4, ANN), BIM	To optimize thermal comfort, enhance energy efficiency, and enable predictive maintenance in buildings through advanced DT frameworks	Real-time monitoring of energy consumption and thermal comfort, prediction and optimization of energy usage, human-centric solutions for occupant well-being	Limited adoption of advanced sensors, lack of focus on subjective occupant perception, need for improved international collaboration	DT, IoT, thermal comfort, energy consumption, AI, ML, occupant well-being	Emphasized the role of DT in integrating occupant-centric data for improved energy optimization, highlighted algorithms like YOLOv4 and ANN for thermal comfort predictions and energy management	Investigate XR for real-time human-environment interactions, develop advanced sensor systems for enhanced environmental data, expand international collaboration
Zahedi et al. (2024)	BIM, DTs, Smart Systems.	To provide a scientometric review of Digital Twin applications in the construction industry, focusing on sustainability goals such as emission reductions.	Smart construction, energy optimization, lifecycle analytics, and carbon footprint reduction.	Data integration complexity and underdeveloped frameworks for smart system adoption.	BIM, construction, critical review, Digital Twin, scientometric analysis, sustainability	Identified major DT contributions to emissions reduction and net-zero targets, highlighting gaps in lifecycle stages (e.g., renovation, demolition).	Development of more robust lifecycle analysis tools and conceptual frameworks to bridge design and operational gaps
Yoon et al. (2024)	BIM, DTs, VIM (Virtual In-situ Modeling)	To enhance building operations and maintenance (O&M) by integrating BIM and DTs through Virtual In-situ	Real-time monitoring, fault detection, and lifecycle management of building systems	Interoperability challenges, reliance on sensor accuracy, need for automated processes	BIM, DTs, VIM, O&M, sustainability, lifecycle optimization	Introduced VIM as a bridge between BIM and DTs for advanced O&M, achieving high accuracy in fault detection and diagnosis	Development of autonomous VIM processes, integration of human behaviors into virtual models, and metadata schema standardization
García-Aranda et al. (2024)	GIS, DTs, IoT	To develop a Digital Twin for a university campus to support urban sustainability and decision-making	Air quality monitoring, solar energy optimization, mobility improvement, resource management	Interoperability issues, accessibility constraints, scalability of data integration	DTs, GIS, urban sustainability, smart campuses	Demonstrated a pilot Digital Twin incorporating GIS data for energy management, mobility analysis, and accessibility evaluation	Further integration of IoT and real-time data for advanced urban sustainability applications
Zhou and Liu (2024)	AI, IoT, DTs, Blockchain	To systematically review the role of digital technologies in energy efficiency and energy integration in smart cities	Climate change adaptation, energy flexibility, energy resilience, renewable energy integration	Interoperability issues, data privacy concerns, high computational demands	AI, IoT, DTs, energy flexibility, resilience, renewable energy	Demonstrated the role of DTs and multi-agent systems in distributed energy management and energy efficiency	Proposed integrating digital technologies for advanced multi-agent energy management and resilience in extreme events
Kazeem (2023)	AI, ML, IoT, BIM, DTs	Enhance energy efficiency, resource management, and lifecycle performance	Renewable energy integration, decarbonization strategies	Interoperability, data integration	AI, IoT, ML, DTs, energy modeling, carbon reduction	DTs for energy system coordination, AI for system optimization	Addressing data security and enhancing interoperability

The word cloud in Figure 1 derived from the research keywords underscores the central role of AI, IoT, and DTs, which are frequently highlighted for their transformative impact on sustainable building design and construction. ML is also a prominent theme, emphasizing its relevance in predictive analytics and optimization. Key concepts such as sustainability, energy efficiency, and energy performance are critical in driving the conversation around environmentally conscious practices. BIM and smart cities reflect the integration of advanced technologies for urban and building management. Emerging topics like blockchain, renewable energy, and smart buildings point to the expanding scope of innovations shaping the future of sustainable architecture.

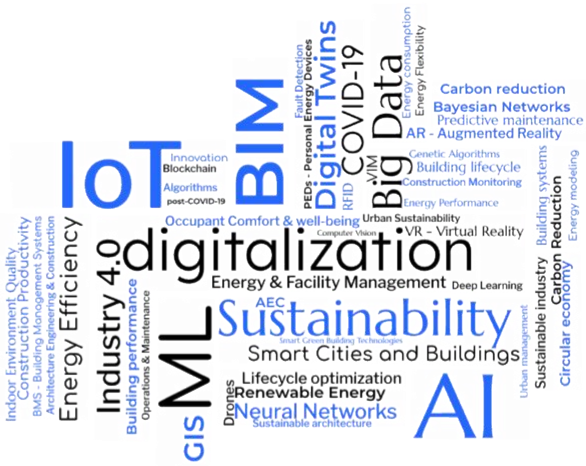

Figure 1. Key technologies and concepts in sustainable building design and the AEC industry (Source: created using Wordclouds.com).

To visualize the trends identified from the literature analysis, the following Figures 2 through 5 present a summary of the key technologies, challenges, and sustainability applications that are shaping the future of the AEC industry in a post-COVID world (Figures 2-5).

4.1. Key Technologies Driving Sustainability

The analysis of the "Technologies Utilized" in sustainable building design post-COVID, as shown in Figure 2, highlights the widespread adoption of key technologies. AI and DTs stand out as the most frequently mentioned in recent research. AI, appearing in 17.28% of studies, and DTs, cited in 16.67%, are pivotal in optimizing building performance, enabling real-time monitoring, predictive maintenance, and resource management. These technologies are especially valuable in post-pandemic building practices, where health, safety, and operational efficiency are of paramount concern. AI, combined with DTs, facilitates the continuous evaluation of building systems and allows for dynamic adjustments that improve energy efficiency and reduce carbon footprints (Gorina et. al.,2024; Yang et. al., 2022). IoT (14.20%) and ML (13.58%) are also critical players in advancing sustainability respectively. These technologies enhance the operational efficiency of buildings by collecting and analyzing real-time data from connected systems, which can optimize energy consumption, automate system adjustments, and reduce waste. The pandemic highlighted the necessity for smarter buildings that can respond to changing environmental and occupancy conditions. The growing use of IoT and ML aligns with this need, supporting not only energy efficiency but also the improvement of building resilience to future disruptions (Gorina et. al.,2024; Martínez-Cuevas et. al., 2024 ; Tokazhanov et. al., 2020; Jogunola et. al., 2022).

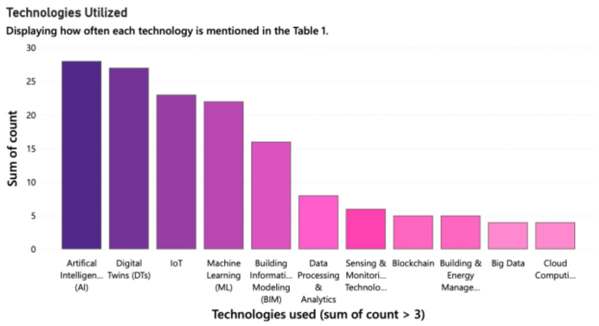

Figure 2. Overview of technologies for sustainability in the AEC industry (Source: Data compiled from Table 1, created using Microsoft Power BI).

Although BIM continues to play a fundamental role in the AEC industry, its prominence has slightly decreased compared to emerging technologies like AI and DTs. BIM, cited in 9.88% of studies, remains integral for coordinating design and construction processes. However, its role has expanded with the integration of more advanced technologies like AI and IoT, which enable the optimization of building performance during operation, making BIM increasingly part of a larger digital ecosystem (Coraglia et. al., 2024). Technologies such as Data Processing & Analytics, Sensing & Monitoring Technologies, and Blockchain have emerged as essential tools for enhancing the sustainability of building systems. These technologies support the efficient use of resources and provide valuable insights into operational performance. Blockchain, for example, is being leveraged to secure transactions and data in smart building systems, ensuring integrity in an increasingly digitalized environment (Tokazhanov et. al., 2020; Yang et. al., 2022). Additionally, more specialized tools like 3D Printing, Cybersecurity, and Geospatial Technologies offer unique solutions to specific challenges. The overall emphasis remains on core technologies like AI and DTs, while innovative tools continue to shape the evolving landscape of sustainable building practices.

4.2. Challenges and Barriers

Despite the promising potential of these technologies, several barriers to their widespread adoption persist. Figure 3 reveals that Interoperability (19.75%) remains the most significant challenge, followed by a variety of other challenges (Others, 16.05%). The integration of diverse systems and technologies, such as IoT devices and DTs, requires compatibility between different platforms, which is often hindered by a lack of universal standards and frameworks (Tokazhanov et. al., 2020). This challenge has become more evident in the post-pandemic context, where buildings need to operate as interconnected ecosystems, managing everything from energy use to occupant health. The inability of various systems to communicate effectively can delay or prevent the realization of full operational efficiency and sustainability goals.

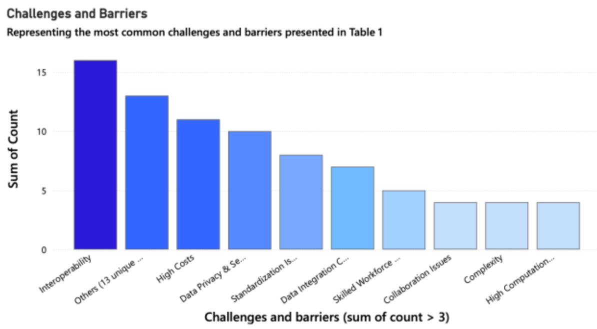

Figure 3. Overview of challenges, and barriers for sustainability in the AEC industry (Source: Data compiled from Table 1, created using Microsoft Power BI).

Another key barrier is the high costs associated with implementing digital technologies (13.58%). These costs, which include purchasing new systems, upgrading infrastructure, and training personnel, can be prohibitive for some organizations. Along with high costs, data privacy and security concerns (12.35%) have also become more pronounced, especially with the increased collection and sharing of sensitive information through IoT sensors and connected building systems. Ensuring the protection of occupant data has become a top priority as more personal information is captured by digital systems. Standardization Issues (9.88%) and Data Integration Challenges (8.64%) highlight the complexities of aligning different systems and managing data effectively. The shortage of skilled workforce (6.17%) and High Computational Demands, Complexity, and Collaboration Issues (4.94%), each reflecting obstacles in the implementation of advanced technologies. Managing and analyzing vast amounts of data generated by IoT systems and DTs requires a high level of expertise. Additionally, the computational power needed for real-time analytics and simulation can strain existing infrastructure, requiring significant investment in both hardware and skilled personnel.

4.3. Focus Areas for Sustainability

The post-pandemic era has intensified the focus on energy optimization and efficiency (26.32%), with real-time monitoring and data analytics (17.54%) at the forefront of this movement (Figure 4). These technologies are crucial for creating buildings that can dynamically adjust to changing conditions, improving both operational efficiency and sustainability. The integration of renewable energy systems (14.04%) is also a significant trend, driven by the growing need to reduce carbon emissions and minimize dependency on non-renewable resources. This shift is particularly relevant in the context of the COVID-19 pandemic, as many organizations seek ways to reduce their environmental impact while also lowering operational costs (Gorina et. al.,2024; Martínez-Cuevas et. al., 2024; Tokazhanov et. al., 2020). Resource efficiency and management (12.28%) and predictive maintenance and lifecycle management (12.28%) have also gained traction as key applications for sustainability. These practices are focused on optimizing resources and extend the lifespan of building systems. Technologies like DTs, AI, and BIM are vital for these applications, as they allow for the proactive management of building systems, reducing waste and improving overall sustainability (Yang et. al., 2022). In addition, smart cities and infrastructure (8.77%) and occupant comfort and well-being (7.02%) have become central to the research agenda. The pandemic highlighted the importance of creating environments that support the health and well-being of occupants, emphasizing the need for buildings that not only function efficiently but also promote occupant safety and comfort. Finally, Smart Construction & Manufacturing (7.02%) and Circular Economy & Sustainability Principles (5.26%) point to forward-thinking approaches in sustainable building practices.

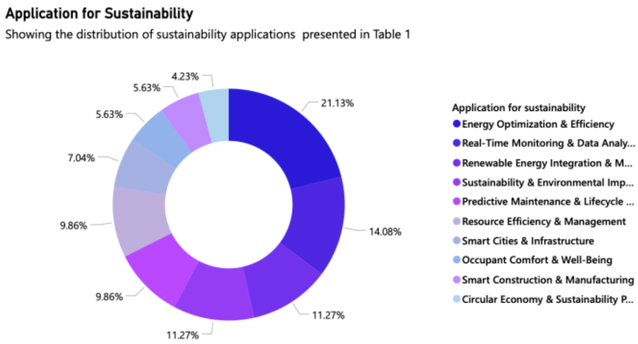

Figure 4. Overview of applications for sustainability in the AEC industry (Source: Data compiled from Table 1, created using Microsoft Power BI).

4.4. Research Trends and Keywords

Research Keywords like AI, IoT, DTs, and ML dominate the research landscape, reflecting the growing importance of these technologies in driving sustainable building practices (Figure 5). Sustainability, energy efficiency, and smart cities are also prominent, highlighting the ongoing shift toward creating more sustainable, resource-efficient urban environments. The continued emphasis on these technologies suggests a future where buildings will increasingly rely on interconnected systems to optimize performance, enhance occupant health, and minimize environmental impact (Gorina et. al.,2024; Martínez-Cuevas et. al., 2024 ; Tokazhanov et. al., 2020; Jogunola et. al., 2022). Future research directions are likely to focus on overcoming the current challenges, particularly interoperability, data privacy, and cost concerns, while expanding the capabilities of existing technologies. As the AEC industry embraces Industry 4.0 and neural networks, the sophistication of building systems will continue to increase, paving the way for more efficient, adaptive, and resilient buildings in the post-pandemic world.

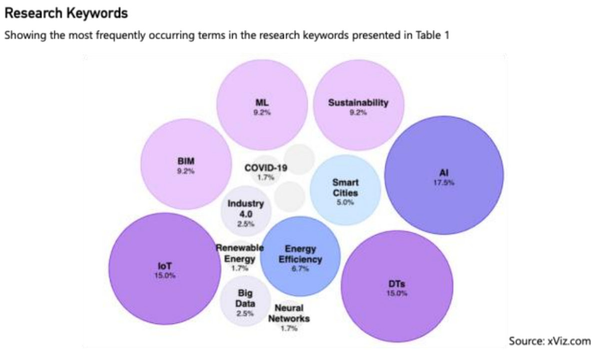

Figure 5. Overview of the most frequent keywords pattern for sustainability in the AEC industry (Source: Data compiled from Table 1, created using Microsoft Power BI and xViz.com).

4.5. Cause and Effect Relationship

There is a clear cause-and-effect relationship between the adoption of digital technologies and the pursuit of sustainability in building design. The growing reliance on

AI, IoT, and DTs is directly linked to the need for more efficient, adaptable, and sustainable building systems. However, the realization of these benefits is contingent upon overcoming the barriers of interoperability, cost, and data privacy. Addressing these challenges will be crucial for enabling the widespread adoption of these technologies, ultimately driving the creation of sustainable, resilient, and health-conscious built environments. In conclusion, the research trends reveal a future where digital technologies will play an integral role in achieving sustainability goals within the AEC industry. While there are challenges to overcome, the promise of energy-efficient, smart, and adaptive buildings continues to drive innovation in building design and operation.

5. Discussion

The future of sustainable building design in the AEC industry will be largely shaped by the ongoing advancement of digital technologies. Emerging innovations such as AI, ML, BIM, DTs, and IoT are becoming increasingly central to sustainability efforts. These tools are driving energy optimization, improving predictive maintenance, enhancing resource management, and enabling real-time monitoring, which collectively increase the resilience and efficiency of buildings. The findings of this study highlight that these technologies offer solutions to global challenges such as climate change, resource scarcity, and the need for post-pandemic recovery strategies (Coraglia, et. al., 2024; Han et. al., 2022; Gorina et. al., 2024).

An important insight from this research is that integrating these technologies also fosters principles of the circular economy, emphasizing waste reduction, material reuse, and lifecycle efficiency. For instance, DTs allow for advanced simulations to optimize energy use, while AI and ML enable data-driven decision-making for minimizing resource consumption. The study by Royan (2021) similarly highlights the increasing use of digital tools such as embodied carbon tracking, life cycle analysis (LCA), IoT, VR, drones, robotics, and 3D printing, emphasizing their role in reducing carbon emissions, enabling hybrid working patterns, and enhancing overall construction efficiency and safety. The future will likely see an increased emphasis on technologies such as 3D printing, robotics, and advanced construction techniques, which will contribute to cost-effective and environmentally sustainable solutions (Strielkowski et. al., 2022).

Royan (2021) further emphasizes the strategic importance of customer-driven sustainability initiatives. Providing stakeholders with real-time visualization of sustainability metrics and implementing sustainability ratings similar to energy efficiency labels can effectively drive behavioral change and informed decision-making towards sustainable building practices. Additionally, robotics and 3D printing technologies present significant socio-economic benefits by enhancing safety, reducing carbon-intensive material use, and addressing labor shortages, thus contributing effectively to long-term industry sustainability.

However, significant barriers remain, including interoperability issues, high implementation costs, and data privacy concerns. Both this study and Royan (2021) underscore the importance of addressing these challenges through supportive policies, institutional frameworks, and collaborative strategies. Governments, industry stakeholders, and researchers must work together to:

- Develop standardized frameworks for data integration and system interoperability,
- Promote regulations for green building certifications and energy-efficient technologies, and
- Invest in capacity-building programs to train a skilled workforce.

In summary, the integration of digital tools with sustainability goals represents a transformative shift for the AEC industry. These advancements will enable buildings to become not only resource-efficient and adaptive but also resilient to global disruptions such as pandemics and climate change. The findings of this study reinforce that the future of sustainable building design depends on both technological innovation and strategic implementation frameworks.

6. Conclusion

The study of sustainable building design and construction in the post-pandemic era reveals the profound impact of digital technologies on the AEC industry. In particular, the integration of technologies such as AI, ML, BIM, DTs, and IoT has reshaped the landscape of sustainable practices by enabling:

- Significant advancements in energy efficiency, predictive maintenance, and lifecycle optimization,
- Improved resource management, reducing material waste and environmental impacts, and
- Enhanced adaptability to emerging global challenges.

This study highlights that the post-COVID shift toward resilience and sustainability accelerated the adoption of digital tools. For instance, BIM has facilitated smarter workflows and integrated design processes, while IoT and DTs have enabled real-time monitoring and scenario simulations to optimize building performance. Royan (2021) similarly emphasizes that digital tools, such as embodied carbon tracking, LCA, robotics, and 3D printing, significantly enhance environmental sustainability, workforce efficiency, and safety, aligning closely with industry priorities. These technologies collectively support data-driven decision-making, improving building efficiency across its lifecycle. Royan (2021) further highlights customer-driven initiatives, including real-time visualization of sustainability metrics and sustainability ratings, as critical to driving informed decisions and promoting behavioral changes toward sustainable building practices.

Nevertheless, challenges persist, including interoperability issues, data privacy concerns, and a shortage of skilled professionals. Addressing these barriers is essential for ensuring the widespread adoption of these technologies. Future studies should focus on overcoming these challenges while exploring the following directions:

- Advancing AI and ML applications to improve predictive modeling and dynamic energy management,
- Developing smart city frameworks that integrate renewable energy systems and connected infrastructures,
- Promoting circular economy principles by leveraging 3D printing and robotics for resource-efficient construction, and
- Exploring interdisciplinary approaches to enhance system interoperability, cybersecurity, and scalability.

In summary, this research underscores that the future of sustainable building design relies on continued technological innovation and strategic adoption of digital tools. By aligning emerging technologies with sustainability imperatives, the AEC industry can build adaptive, energy-efficient, and health-conscious environments capable of addressing climate change, resource scarcity, and future global crises. The successful integration of AI, IoT, and other cutting-edge technologies will drive transformative changes, ensuring a resilient and sustainable built environment in an evolving world.

Author Contributions

The percentages of the author' contributions are presented below. The author reviewed and approved the final version of the manuscript.

	A.S.S.
C	100
D	100
S	100
DCP	100
DAI	100
L	100
W	100
CR	100
SR	100
PM	100
FA	100

C=Concept, D= design, S= supervision, DCP= data collection and/or processing, DAI= data analysis and/or interpretation, L= literature search, W= writing, CR= critical review, SR= submission and revision, PM= project management, FA= funding acquisition.

Conflict of Interest

The author declared that there is no conflict of interest.

Ethical Consideration

Ethics committee approval was not required for this study because of there was no study on animals or humans.

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