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A Systematic Review of Autonomous Technologies and their Applications for Sustainable Built Environments

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ABSTRACT: As the built environment faces growing sustainability and resilience challenges, autonomous technologies (AT) have emerged as promising tools for adaptive and data-driven decision-making. Powered by artificial intelligence (AI), these systems can operate with minimal human intervention and hold the potential to transform how buildings, infrastructure, and urban systems are managed. This study presents a systematic review of 39 peer-reviewed articles published between 2015 and 2024 that explicitly link AT to sustainability outcomes in the built environment. The review categorizes AT applications into five key domains: energy management, climate resilience, construction automation, building operation and maintenance, and urban infrastructure and smart cities. For each domain, we explore the ways in which AT is being utilized to support environmental, economic, and social aspects of sustainability. Our findings reveal that while AT adoption is expanding, its implementation remains fragmented and primarily focused on operational efficiency. Social and economic sustainability considerations are often overlooked. By synthesizing current knowledge and proposing directions for future research, this study contributes to advancing the role of AT in creating more integrated, resilient, and sustainable built environments.

1. INTRODUCTION

The built environment comprises human-made buildings and infrastructure that serve as physical settings for human activities (Seyedrezaei et al., 2023). With the global population projected to reach around 9 billion by 2050 and the building floor area expected to double by 2060 (IEA, 2017), the environmental, social, and economic impacts of the built environment are expected to intensify. These challenges underscore the urgent need for transformative solutions to enhance the sustainability of the built environment while accommodating rapid population growth.

Sustainability generally includes three key dimensions: environmental protection, economic efficiency, and social well-being (Gimenez et al., 2012). Integrating these multifaceted goals is essential to developing built environments and necessitates a holistic approach throughout the entire lifecycle, including design, construction, operation, and end-of-life stages. However, the current built environment remains far from sustainable across all three dimensions. Environmentally, the built environment remains a significant contributor to climate change, accounting for over 40% of annual global CO_2 emissions (Burns et al., 2024). Economically, the construction industry is known for its low productivity and limited adaptability, largely due to its traditional and fragmented nature, which results in persistent inefficiencies and high operational costs (Van, 2024). Socially, many built environments fail to meet diverse occupant and community needs, resulting in poor indoor and outdoor environmental quality, limited accessibility, and inequitable distribution of resources and services (Wang & Ke, 2024).

The built environment is inherently dynamic, constantly shaped by changing environmental conditions, user behaviors, and patterns of urban development. These ongoing changes introduce uncertainty and require systems to continuously adapt to new situation (Hassler & Kohler, 2014). Given this complexity, traditional human-centered approaches often struggle to respond effectively or coordinate responses in an integrated manner. In this context, autonomous technologies (AT) emerge as a transformative solution. Powered by advances in artificial intelligence (AI), AT has received growing attention in the field of Civil and Construction Engineering (C&CE). These systems are designed to perform tasks, make decisions, and adapt to changing conditions with minimal or no human intervention (Watson & Scheidt, 2005). By leveraging these capabilities, AT can reshape how the built environment is managed, enabling it to operate more sustainably while supporting the triple bottom line of environmental, economic, and social outcomes.

This review paper explores the role of AT and their applications in the C&CE fields to foster a more sustainable built environment. When integrated with advanced technologies such as the Internet of Things (IoT), sensors, and robotics, AT can address inefficiencies and environmental challenges across all lifecycle stages. The overarching goal of this review is to highlight how AT not only contributes to sustainability but also drives innovation and resilience throughout the built environment.

2. RESEARCH BACKGROUND

Achieving sustainability in the built environment, across buildings, infrastructure, and urban systems, requires more than isolated technological upgrades. While the environmental, economic, and social goals of sustainability are well recognized (WGBC, 2025), current practices often rely heavily on conventional, human-driven processes that struggle to respond to complex and evolving demands. Traditional approaches to design, construction, and management lack the flexibility and responsiveness required to address dynamic environmental conditions, resource constraints, and the needs of diverse users.

In response, a growing body of research points to the need for a paradigm shift toward systems that can autonomously operate, adapt, and optimize their performance. As Cugurullo (2020) highlights, AI-enabled systems such as autonomous vehicles, robotic assistants, and urban-scale governance platforms are already reshaping how cities and infrastructure are managed. These technologies are capable of learning from their environments and making context-aware decisions, opening new possibilities for adaptive and resilient urban systems. In this study, we define AT as systems that are capable of perceiving their environment, analyzing data, and making decisions or taking actions with minimal human intervention. While many ATs are built upon AI, not all AI applications are autonomous. Therefore, this review includes only those technologies that demonstrate a certain degree of self-governance, adaptability, or autonomous control beyond rule-based automation or passive data processing. This distinction informed the selection of studies for this review in Chapter 3, focusing on applications where autonomy plays a central role in how the system operates and contributes to sustainability outcomes.

In the context of the built environment, however, the implementation of AT remains limited in scope. Most existing applications focus on automation or performance monitoring (e.g., detecting structural anomalies or issuing maintenance alerts) without fully integrating sustainability as a core design objective (Aghaei, 2022; Macaulay & Shafiee, 2022). While these capabilities improve efficiency, research on AT for sustainability in the built environment remains limited. As a result, there is a gap between the theoretical potential of AT and its practical application in promoting holistic sustainability. Bridging this gap requires a comprehensive understanding of how AT is currently used and how it can be more effectively deployed to address sustainability goals across multiple domains. To this end, this study conducts a systematic review of existing literature that explicitly links AT with sustainability in the built environment, identifying key trends, challenges, and research opportunities.

3. RESEARCH METHODS

This study follows the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) framework for conducting a systematic review of autonomous technologies for sustainable built environment. We used the search term *"(Autono* AND Tech*) AND (Sustain*) AND (Built environment OR civil OR construction)"* in the Web of Science Database Core Collection, which yielded 3,054 research papers.

Out of the 3,054 articles initially identified, exclusions were made based on the following criteria: (1) Not a peer-reviewed journal article (n = 450), (2) Not written in English (n = 50), (3) Published outside the 2015-2024 timeframe (n = 130), and (4) Irrelevant to the study (n = 2,340). The 2015-2024 period was selected as it represents a critical decade in which global sustainability efforts (United Nations, 2015), and rapid advancements in AI, especially in deep learning, began to converge and influence research across various domains. Regarding irrelevance, specific criteria were established for the term "autonomous technology," which was defined as systems or tools capable of performing tasks, making decisions, or adapting to changing conditions with minimal or no human intervention. These technologies leverage advanced computational techniques, such as AI, machine learning, and sensor-driven data analytics, to enable automated sensing, analysis, and optimization. Based on this definition, many articles focused solely on Autonomous Vehicles (AVs) were excluded unless they addressed the integration of AVs within transportation systems utilizing autonomous technologies. Additionally, papers using the term "autonomous" to refer to "autonomous regions" were excluded. This study further prioritized articles focusing on sustainability as a primary objective. The research targeted the built environment, encompassing buildings, infrastructure, and urban systems across all construction stages—design, construction, operations and maintenance (O&M) and renovation. As a result, 2,971 articles were excluded.

Among 84 full-texts, two eligibility criteria were applied to exclude the data: (1) full-text is not accessible and (2) research scope is out of using AI-driven AT in C&CE fields. Finally, 38 full-text articles including 11 review articles were reviewed in this study. This process is shown in Figure 1. Table 1 in the Appendix provides a detailed list of the reviewed articles.

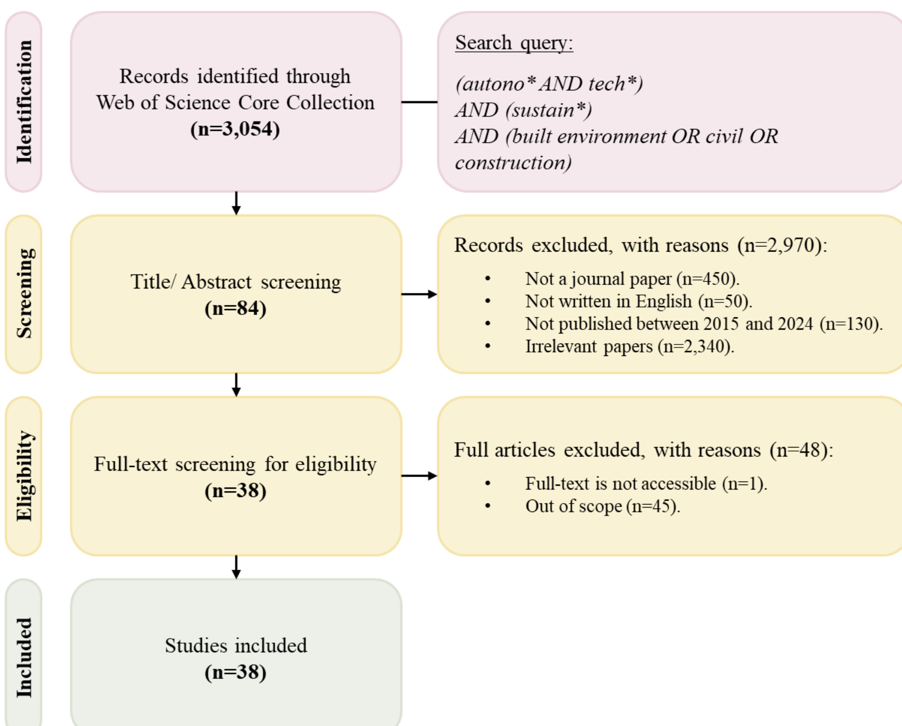

Figure 1. PRISMA Framework for systematic review

A keyword co-occurrence network was generated using VOS viewer to analyze the selected literature's thematic structure. The full text of the 38 reviewed articles was processed, and Binary Counting was applied to identify key terms and their relationships. After initial processing, unrelated general terms (e.g., "research trend," "systematic literature review," "future direction") were manually excluded. The network visualization revealed four major clusters, as shown in Figure 2.

First, the blue cluster was further categorized into energy management and climate resilience, reflecting the dual focus on energy efficiency and resilience to environmental changes. The yellow and green clusters predominantly featured keywords related to construction automation and building operation & maintenance, supporting their classification as distinct domains. The red cluster, containing keywords such as "smart city," "autonomous vehicle," and "government," corresponded with the urban infrastructure & smart cities category. By structuring the review based on these five domains, this study systematically captures how autonomous technologies contribute to sustainability across different scales of the built environment.

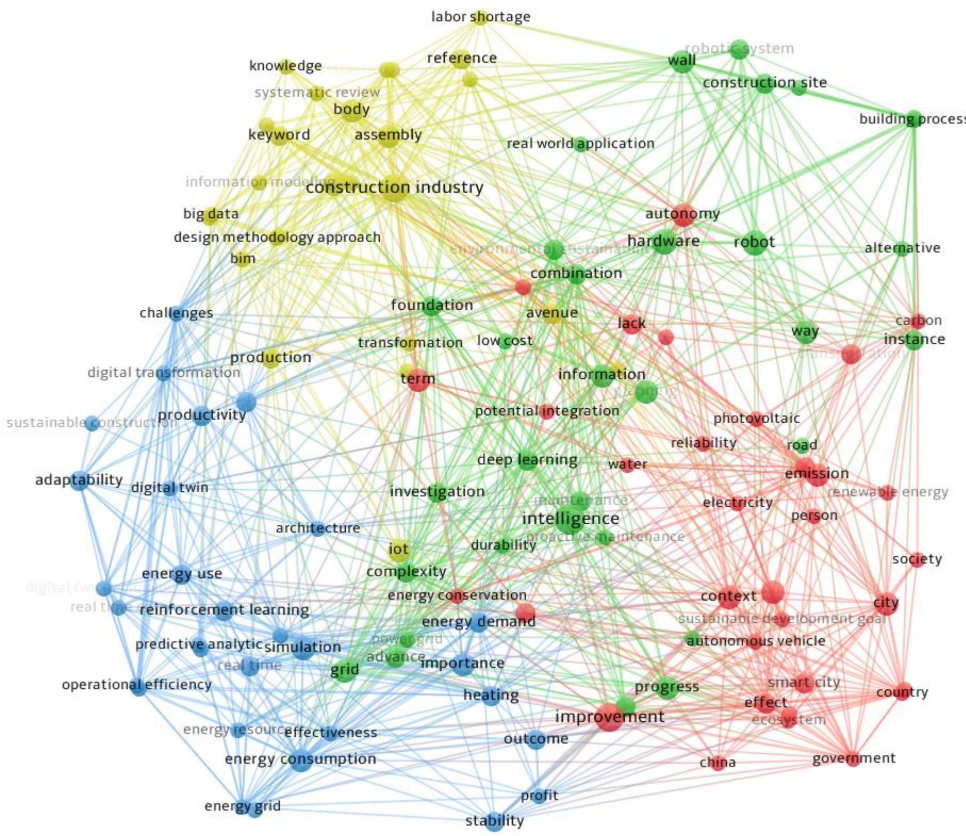

Figure 2. Frequent terms in reviewed literatures

4. APPLICATION AREA OF AUTONOMOUS TECHNOLOGIES

AI is at the core of autonomous technologies, driving innovation across various domains. A systematic review reveals that AI is rarely implemented in isolation; rather, it is integrated with complementary technologies such as IoT, sensors, and robotics. This integration enables autonomous systems to perceive, analyze, and act within dynamic environments, enabling real-world autonomy. This section explores key application areas where AI-driven autonomy is transforming industries, including Energy Management, Climate Resilience, Construction Automation, Building Operation & Management, and Urban Infrastructure & Smart Cities. Each domain demonstrates how AI-powered autonomy reshapes decision-making processes, optimizes performance, and fosters sustainability in the built environment.

4.1 Energy Management

Autonomous technologies are revolutionizing energy management by integrating AI-driven techniques such as machine learning, deep learning, IoT, and predictive analytics. These technologies facilitate real-time decision-making, predictive maintenance, and decentralized optimization, allowing energy systems to dynamically respond to fluctuations, enhance efficiency, and reduce reliance on carbon-intensive sources.

Pong et al. (2021) introduced Cyber-Enabled Grids (CEGs), integrating IoT, AI-driven analytics, and decentralized decision-making to optimize bidirectional energy flow. Similarly, SaberiKamarposhti et al. (2024) applied deep learning techniques to hydrogen-based smart grids, optimizing hydrogen production, distribution, and storage while ensuring grid resilience. AI is also advancing energy demand forecasting, as demonstrated by Zhang et al. (2024), who applied deep reinforcement learning (DRL) to real-time adaptation of grid fluctuations, minimizing operational costs. For photovoltaic (PV) plants, AT enhances fault detection, power prediction, and maintenance efficiency. Emamian et al. (2022) developed an IoT-based Intelligent Monitoring System (IMS) utilizing deep ensemble learning for system failure detection and power forecasting. Meanwhile, Kolahi et al. (2024) introduced an AI-powered aerial monitoring system for PV plants, leveraging robotics, image analysis, and IoT connectivity for real-time fault detection and predictive analytics. AI-driven autonomous energy systems also optimize energy use in buildings. Casals et al. (2016) implemented adaptive AI-based control systems in underground stations, optimizing lighting, ventilation, and escalator operations to achieve significant energy savings. Liao et al. (2023) developed an automated multi-energy system (MEMS) for residential buildings, integrating deep learning models to predict household energy consumption, optimize renewable energy use, and reduce grid dependence. Collectively, these advancements illustrate how AI-driven AT enhances energy efficiency, from large-scale smart grids to localized building applications, accelerating the transition toward low-carbon energy systems.

The reviewed applications in energy management primarily contribute to environmental sustainability by enhancing energy efficiency, integrating renewable sources, and reducing reliance on carbon-intensive grids. Economically, AI-enabled optimization reduces operational costs and improves energy demand forecasting, offering long-term financial benefits for both utilities and users. However, social sustainability is less explicitly addressed, as few studies consider issues such as equitable access to intelligent energy systems or the inclusivity of user-centered energy controls.

4.2 Climate Resilience

With climate change intensifying, the built environment must adapt to increasing environmental risks such as extreme weather events, rising temperatures, and resource scarcity. Intelligent systems powered by AI support this adaptation by enabling real-time monitoring, predictive analytics, and decentralized decision-making (Al-Raeei, 2024). These capabilities contribute to improved energy use, urban cooling, and stormwater management

At the building scale, Mohammadi and Bahman (2024) proposed a sustainable energy-autonomous building (AB) model optimized for hot climates, using the 5Z framework: Zero-carbon, Zero-energy, Zero-grid connections, Zero energy bills, and Zero-emission mobility. Beyond buildings, AI-powered AT contributes to urban climate resilience by mitigating heat stress and managing water systems more efficiently. Goddard et al. (2021) demonstrated that automated irrigation systems can optimize urban cooling, while Shishegar et al. (2021) developed a real-time control (RTC) framework using IoT for stormwater management. Nik and Moazami (2021) also introduced a Collective Intelligence-based demand-side management system that allows buildings to regulate energy use autonomously during extreme climate events.

These applications primarily promote environmental sustainability by improving adaptability to climate stressors and reducing emissions during peak conditions. On the economic side, technologies such as smart irrigation and energy demand management enhance resource efficiency and reduce operational costs. Although social sustainability is indirectly supported through improved urban comfort and risk reduction, aspects such as equitable access and community-level resilience remain underexplored.

4.3 Construction Automation

Construction 4.0, an extension of Industry 4.0, integrates digitalization, automation, and AI-driven decision-making to improve efficiency, safety, and sustainability in construction (Shafei et al., 2023; Statsenko et al., 2022). One key advancement is Collective Robotic Construction (CRC), where multi-robot systems collaborate to autonomously assemble structures with minimal human intervention (Petersen et al., 2019). Leder et al. (2022) a modular robotic construction system that integrates building materials as part of its robotic mechanism, enabling scalable, autonomous assembly. Similarly, Mascaro et al. (2021) introduced a robotic system capable of handling irregular materials, such as natural stones, through LiDAR-based mapping and AI-driven grasp planning, demonstrating the feasibility of robotic construction in unstructured environments. Beyond assembly, robotic excavation and on-site automation are playing an increasing role in autonomous construction. Johns et al. (2023) developed a 12-ton robotic excavator that autonomously detects, manipulates, and places stones, facilitating large-scale dry-stack wall construction. Likewise, Jud et al. (2021) introduced HEAP, an autonomous walking excavator equipped with GNSS-RTK localization and LiDAR perception, capable of trenching, material handling, and robotic excavation. In parallel, modular construction and AI-assisted prefabrication are revolutionizing building assembly. Liu et al. (2024) developed a discrete modular construction system using self-interlocking SL-Blocks, which leverage machine learning and reinforcement learning to enable robotic assembly, disassembly, and reconfiguration. This approach enhances construction adaptability and resource efficiency, aligning with the broader goals of sustainable and automated construction (Kor & Yitmen, 2023). To enhance lifting and logistics, Xiong et al. (2024) proposed a Service-Oriented Autonomous Crane System (SACS) that integrates AI-powered predictive maintenance and real-time monitoring, improving safety and operational efficiency.

AT applications in construction automation primarily support environmental and economic sustainability. Robotics and AI-enhanced prefabrication reduce material waste, increase resource efficiency, and improve precision, contributing to lower carbon footprints. Economically, automated systems enhance productivity, reduce labor costs, and mitigate schedule delays, offering long-term cost benefits. However, social sustainability remains underexplored, particularly in relation to labor displacement, workforce reskilling, and broader implications for employment equity in the construction sector.

4.4 Operation & Maintenance

The integration of AI with various tools is transforming the operation and maintenance (O&M) of the built environment. These technologies enable predictive maintenance, real-time monitoring, and autonomous fault detection, enhancing efficiency, sustainability, and cost-effectiveness while minimizing downtime and operational risks (Mousavi et al., 2024; Sadoughi et al., 2024). For example, Dey et al. (2023) introduced an imitation learning-enhanced reinforcement learning (RL) approach for autonomous building control, optimizing energy efficiency, occupant comfort, and grid flexibility. Similarly, Zhang et al. (2023) developed an adaptive HVAC system using AI-based simulations and computational fluid dynamics (CFD), achieving 30% energy savings while maintaining indoor air quality. These studies demonstrate how AI-driven automation enhances building performance and operational efficiency. Beyond building-specific applications, AI-powered facility automation is advancing. Kee et al. (2022) designed a multi-functional smart home integrating IoT, cloud computing, and decision support systems (DSS) to achieve zero-emission operation for three autonomous days, supporting trends in self-sufficient and autonomous facility management (Musarat et al., 2022). For structural safety, Li et al. (2024) developed a mechanics-informed autoencoder (MIAE) for real-time structural health monitoring (SHM), improving damage detection accuracy by 35%. Similarly, Birgin et al. (2022) introduced a self-sensing asphalt pavement system that uses AI-powered predictive maintenance to detect and optimize traffic load monitoring, enhancing infrastructure reliability and long-term maintenance. Despite these advancements, data security, system integration, and scalability remain to achieve fully autonomous O&M solutions (Osunsanmi et al., 2023; Liu et al., 2022; Haiyirete et al., 2024).

AT in operation and maintenance contributes strongly to environmental and economic sustainability by improving energy efficiency, reducing system failures, and enabling predictive maintenance that minimizes resource waste. Economically, these technologies lower long-term operational costs, reduce unplanned downtime, and improve system reliability. In terms of social sustainability, improvements in occupant comfort, indoor environmental quality, and safety are evident, though broader issues such as data privacy and the digital divide remain underexplored in current research.

4.5 Urban Infrastructures and Smart city

AI-driven autonomous technologies are reshaping urban infrastructures, optimizing mobility, maintenance, and energy management to enhance efficiency and sustainability. In urban mobility, Kővári et al. (2024) proposed a multi-agent reinforcement learning-based highway control system, dynamically adjusting speed limits to improve traffic flow and lower emissions. Similarly, Abbas et al. (2023) developed an IoT-enhanced autonomous parking system, integrating AI-based image recognition to optimize parking space detection, ultimately reducing congestion and improving urban accessibility. For infrastructure maintenance, AT is shifting conventional approaches from reactive to proactive strategies. Pham et al. (2024) introduced an AI-driven road quality assessment system, leveraging real-time data to detect surface deterioration before it leads to major structural failures. This predictive capability enhances urban resilience by reducing maintenance costs and improving road safety. Beyond land-based infrastructure, AI-driven automation is transforming smart seaports, integrating real-time logistics optimization and marine renewable energy solutions to enhance efficiency and sustainability (Clemente et al., 2023). These innovations align with the broader goals of autonomous urban infrastructure and energy transition. In urban logistics, autonomous drone technology is becoming increasingly prevalent. ElSayed et al. (2022) introduced an AI-powered UAV charging network, utilizing solar energy from building envelopes to power autonomous drones. This innovation not only reduces energy costs but also significantly lowers emissions, contributing to more sustainable urban logistics systems. As these technologies continue to evolve, future research highlights the need for interdisciplinary, data-driven approaches to enhance cyber-physical systems (CPS) in urban settings, ensuring resilient and adaptive infrastructures (Broo et al., 2021).

AT in urban infrastructure primarily advances environmental sustainability by reducing emissions through optimized mobility, renewable energy integration, and energy-efficient logistics. Economically, predictive maintenance and smart logistics lower operational costs and enhance infrastructure longevity. While some applications improve accessibility and urban safety, social sustainability remains underdeveloped in terms of equitable access, digital inclusion, and public engagement in smart city systems.

5. DISCUSSION AND CONCLUSIONS

Autonomous technologies (AT) are transforming the built environment by enhancing sustainability, resilience, and efficiency across its lifecycle. Their contributions span energy management, climate adaptation, automated construction, building operations, and urban infrastructure. However, a closer examination of existing studies reveals that AT implementations often remain fragmented and narrowly focused. Many applications target specific functions or subsystems, such as optimizing HVAC performance or automating construction tasks, rather than supporting integrated, system-wide sustainability.

When analyzed through the lens of the triple bottom line—environmental, economic, and social—this fragmentation becomes more evident. Most AT applications strongly emphasize environmental sustainability, such as improving energy efficiency, reducing emissions, and optimizing resource use. For example, in energy management, AI-enhanced systems optimize consumption and improve grid responsiveness, but few studies consider the economic scalability of these solutions or their accessibility across different socio-economic groups. In construction automation, robotics and AI-driven systems improve efficiency and reduce waste, yet the implications for labor displacement, workforce adaptation, and long-term economic impacts are often overlooked. Social sustainability is particularly underrepresented, as few autonomous systems are designed with occupant comfort, accessibility, or equity in mind, all of which are essential for inclusive and resilient urban development.

These gaps suggest that AT in the built environment is still largely approached as a collection of technical solutions focused on performance improvement, rather than as a framework for achieving multidimensional sustainability. To transition from partially autonomous systems to integrated and sustainable built environments, several key challenges must be addressed. First, AI-driven decision-making should evolve beyond static or predictive modes toward real-time, adaptive control that allows systems to respond to changing conditions and feedback from their environment. This requires more advanced reinforcement learning models and self-learning algorithms. Second, future research should focus on developing integrated, cross-domain AT ecosystems where energy, construction, maintenance, and urban systems interact dynamically and autonomously. For instance, an intelligent building should be capable of managing its own energy use while also interacting with decentralized energy grids, responding to climate stressors, and adapting to user needs in real time. Therefore, integrating comprehensive sustainability assessments into AT development is essential to ensure that autonomous decision-making supports long-term environmental, economic, and social outcomes. While the potential of AT to improve efficiency is clear, it is also important to recognize that certain applications may lead to unintended consequences, such as rebound effects, where efficiency gains encourage increased use. Understanding and managing such sustainability risks will be an important direction for future research.

This review contributes to this broader understanding by providing a structured overview of how AT is currently used and by offering a comprehensive understanding of how AT can be more effectively deployed to address sustainability goals across multiple domains. By reimagining AT as more than a collection of automation tools, but rather as an enabler of sustainability transformation, the built environment can progress toward becoming an adaptive, intelligent, and equitable system.

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APPENDIX

Table 1: Reviewed papers

	Paper	Application area
1	Abbas et al., 2023	Urban Infrastructures and Smart city
2	Birgin et al., 2022	O&M
3	Broo et al., 2021	Urban Infrastructures and Smart city
4	Casals et al., 2016)	Energy Management
5	Clemente et al., 2023	Urban Infrastructures and Smart city
6	Dey et al., 2023	O&M
7	ElSayed et al., 2022	Urban Infrastructures and Smart city
8	Emamian et al., 2022	Energy Management
9	Goddard et al., 2021	Climate Resilience
10	Haiyirete et al., 2024	O&M
11	Johns et al., 2023	Construction Automation
12	Jud et al., 2021	Construction Automation
13	Kee et al., 2022	O&M
14	Kolahi et al., 2024	Energy Management
15	Kor & Yitmen, 2023	Construction Automation
16	Kővári et al., 2024	Urban Infrastructures and Smart city
17	Leder et al., 2022	Construction Automation

18	Li et al., 2024	O&M
19	Liao et al., 2023	Energy Management
20	Liu et al., 2022	O&M
21	Liu et al., 2024	Construction Automation
22	Mascaro et al., 2021	Construction Automation
23	Mohammadi & Bahman, 2024	Climate Resilience
24	Mousavi et al., 2024	O&M
25	Musarat et al., 2023	O&M
26	Nik & Moazami, 2021	Climate Resilience
27	Osunsanmi et al., 2023	O&M
28	Petersen et al., 2019	Construction Automation
29	Pham et al., 2024	Urban Infrastructures and Smart city
30	Pong et al., 2021	Energy Management
31	SaberiKamarposhti et al. 2024	Energy Management
32	Sadoughi et al., 2024	O&M
33	Shafei et al, 2023	Construction Automation
34	Shishegar et al., 2021	Climate Resilience
35	Statsenko et al., 2022	Construction Automation
36	Xiong et al., 2024	Construction Automation
37	Zhang et al., 2023	O&M
38	Zhang et al., 2024	Energy Management