Journal of Building Engineering 104 (2025) 112347

Contents lists available at ScienceDirect

Journal of Building Engineering

journal homepage: www.elsevier.com/locate/jobe

IoT driven building automation systems: A review on energy efficiency, occupant comfort, and sustainability

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ARTICLE INFO

Keywords:
IoT-BAS
Energy efficiency
User comfort
CO_2 reduction
Sustainability

ABSTRACT

Building Automation Systems (BAS) are widely used to enhance energy efficiency in buildings. Due to rigid control mechanisms, conventional BAS lacks adaptability and real-time responsiveness. Integrating the Internet of Things (IoT) with BAS empowers real-time monitoring, data-driven automation, and smart decision-making. This advancement greatly improves energy efficiency, occupant comfort, and Carbon dioxide (CO_2) reduction, which are critical factors for sustainable and smart buildings. However, existing studies lack analysis of these critical factors in a unified framework. Hence, this research reviews the 117 articles released from 2010 to 2023 to examine the nexus between IoT and BAS considering these factors. Moreover, this study systematically evaluates the IoT-driven BAS in three critical areas: energy efficiency, indoor user comfort, and CO_2 reduction in smart buildings. Additionally, it addresses the key challenges in implementing IoT-BAS concerning interoperability, security, and scalability. The findings of this research unveil that IoT-BAS greatly improves energy efficiency, human comfort, and emission reduction through continuous monitoring, predictive analytics, and intelligent automation. The IoT-driven techniques like occupancy-based Heating, Ventilation and Air Conditioning (HVAC) control, smart lighting, and predictive maintenance greatly minimize energy usage while enhancing indoor environmental quality. Furthermore, this study identifies standardized communication protocols, strong security frameworks, and hybrid cloud-edge architectures as efficient remedies aiding the IoT-BAS integration. This unique, challenge-driven research framework provides valuable insights to building engineers, facility managers, and policymakers advancing IoT-driven smart buildings while supporting sustainability goals. Future research should focus on AI-driven BAS, open interoperability, blockchain-based advanced cybersecurity, and digital twins for highly resilient IoT-BAS.

Nomenclature			
This review article uses the following abbreviations			
BAS	Building Automation System	PECS	Personal Environment Control System
IoT	Internet of Things	NB	Narrow Band
BMS	Building Management System	RF	Radio Frequency

(*continued on next page*)

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https://doi.org/10.1016/j.jobe.2025.112347
Received 27 July 2024; Received in revised form 26 February 2025; Accepted 12 March 2025
Available online 14 March 2025

(*continued*)

Nomenclature			
This review article uses the following abbreviations			
BEMS	Building Energy Management System	PIR	Passive Infra Red
BA	Building Automation	IR	Infra Red
SLR	Systematic Literature Review	HTTP	Hypertext Transfer Protocol
PRISMA	Preferred Reporting Items for Systematic Reviews and Meta-Analyses	MQTT	Message Queuing Telemetry Transport
PLC	Programmable Logic Controller	API	Application Programming Interface
RTU	Remote Terminal Unit	LoRaWAN	Long Range Wide Area Network
LAN	Local Area Network	HVAC	Heating Ventilation and Air Conditioning
GB	Green Buildings	DTLS	Datagram Transport Layer Security
SEM	Smart Energy Management	PCS	Personal Communication Services
IAQ	Indoor Air Quality	OPC UA	Open Platform Communication Unified Architecture
IEQ	Indoor Environment Quality	ISO	International Organisation for Standardization
ARM	Advanced Risc Machines	IEC	International Electrotechnical Commission
CoAP	Constrained Application Protocol	ITU	International Telecommunication Union
BIM	Building Information Modeling	IDS	Intrusion Detection System
BACnet	Building Automation and Control Network	SSL	Secure Sockets Layer
Lon Works	Local Operating Networks	TLS	Transport Layer Security
KNX	Konnex	IEEE	Institute of Electrical and Electronics Engineers
DSM	Demand Side Management	UETA	Uniform Electronic Transaction Act
EMS	Energy Management System	ESIGN	Electronic Signatures in Global and National Transactions Act
FM	Facility Management	TEE	Trusted Execution Environments

1. Introduction

Buildings account for 30 % of the total energy consumed worldwide and contribute to 26 % of total emissions, of which 8 % are direct emissions from buildings and 18 % are indirect emissions from heat generation and electricity used in buildings [1]. Moreover, building energy consumption rises due to adverse weather, global warming, and urbanization in developing nations [2]. This growing need for energy and environmental concerns urges energy-efficient operation, sustainability, and occupant well-being as critical concerns in modern buildings. BAS has been increasingly used to control HVAC, lighting, and indoor environmental quality. It provides centralized and automatic control over a building's electrical systems, lighting, shading, access, security, and other interrelated systems. It is also termed a Building Management System (BMS) or Building Energy Management System (BEMS) [3]. BAS has been widely employed in commercial structures, shopping centers, industrial settings such as factories, and even residential homes since it achieves energy savings in commercial buildings through centralized control and monitoring [4,5]. To effectively support building operations, BAS architecture consists of three layers: field layer, automation layer, and management layer [6]. The field layer is the lowest stratum, where communication occurs with field instruments (sensors, actuators). The automation layer is the middle one that processes measurements. At the top is the management layer, where system data presentation, forwarding, trending, logging, and archival occur [7]. For the effective functioning of BAS, seamless communication between its various layers is crucial. To achieve communication between different system components like sensors, controllers, and actuators, BAS uses standardized communication protocols that enable effective communication between different devices and platforms.

Findings from the previous study [8] indicate that the most often used communication protocols in BAS are BACnet, Lon Works, KNX, and Modbus. BACnet (Building Automation and Control Network) is a commonly used open protocol that integrates HVAC, lighting, security, fire detection, and several other systems in a building, making it a popular option for large-scale automated projects [9]. Lon Works (Local Operating Network) made by Echelon Corporation is another important and sophisticated protocol engineered particularly for decentralized control facilitating communication among devices across various communication mediums including twisted pairs, power lines, and wireless networks [10]. In contrast, KNX (Konnex) is a renowned worldwide standard protocol used for home and building automation. It is flexible in controlling lighting, shading, HVAC, and security systems while bolstering many communication media, including Ethernet, RF (Radio Frequency), and twisted pair cables [11]. Modbus was initially designed for industrial automation, but now it has been extensively embraced in BAS because of its simplicity and efficiency in data exchange between controllers, sensors, and actuators across TCP/IP (Transmission Control Protocol/Internet Protocol) networks [12].

These protocols are essential for the efficient management and control of various building systems. However traditional BAS relies solely on the routine activities of its inhabitants for operation. The behavior and preferences of the occupants are not considered. [13]. Meanwhile, IoT utilization in buildings facilitates real-time monitoring and adaptive control based on occupant preferences and indoor climate, ensuring improved comfort and energy efficiency. [14]. Moreover, it is a global network of individually addressable items consisting of sensing and actuating devices that allow information to be shared across platforms. It uses a single, unified architecture, creating a shared operating model to support creative applications [15]. Furthermore, it enables intelligent objects to speak with one another for efficient real-world information and data transfer. These Intelligent objects with sensor interactive features and user identification technologies enable more real-world data collection, thereby assisting advanced automation [16].

Thus, the integration of IoT with BAS enables remote management capabilities, allowing building managers to supervise and modify processes from any location with an internet connection [17]. This flexibility enhances operational excellence and permits systematic servicing to address issues before they escalate. It also empowers occupants to personalize their environment and adjust settings according to their preferences, which enhances comfort and satisfaction. Beyond general comfort, visual and thermal comfort is also crucial for occupant well-being and better indoor experience. Various aspects of visual and thermal comfort in smart buildings were discussed in previous studies, such as adaptive occupant behavior, which could achieve comfortable and energy-efficient indoor space [18]. Studies also suggest using adaptive facades and double-sided material geometries to improve visual and thermal qualities by adjusting the building envelopes depending on user positions and the indoor environment [19]. Furthermore, using multipurpose roller shade controllers to improve indoor comfort and reduce energy loads is also discussed in research [20]. Besides these studies supporting passive and semi-automated comfort strategies, the IoT-BAS significantly improves their efficacy through real-time sensor-based automation that is highly adaptable to occupant needs.

Additionally, IoT-BAS facilitates the incorporation of alternative energy and participation in smart grid initiatives, enabling buildings to dynamically adjust energy demand dependent on grid dynamics and price trends. By reducing energy consumption and emissions, IoT-enabled buildings play a pivotal role in switching to a carbon-neutral economy and reaching climate action targets [21]. Moreover, other methods to reduce CO_2 emissions have been analyzed in previous studies. One such approach involves using less cement material like fiber-reinforced concrete [22] and cementless materials like high-performance alkali-activated concrete and geopolymer concrete [23]. These materials reduce the carbon footprint related to conventional cement production. However, the integration of IoT-based structural monitoring and smart building automation further improves the productivity, strength, and energy efficiency of these substances. Through real-time data analytics, flexible HVAC control, and predictive maintenance, IoT-BAS assures that buildings built with alternative materials sustain optimal thermal comfort and operational competence throughout their life span.

While the potential of IoT technologies helps to transform building operations and contribute to sustainability goals, there remains a lack of in-depth analysis on critical factors like energy efficiency, occupant comfort, and CO_2 reduction in a unified framework for IoT-BAS. Specifically, this research aims to bridge these gaps by thoroughly reviewing IoT-based BAS for energy, comfort management, and sustainability and also addresses the interoperability, security, and scalability challenges associated with IoT-BAS integration. Further, this research explores the following research questions.

1. What are the recent advancements in IoT-based BAS?
2. How can IoT technologies be leveraged to optimize energy consumption, CO_2 reduction, and occupant comfort in BAS?
3. What are the key challenges faced by implementing IoT-based BAS, particularly regarding interoperability, security, and scalability?
4. What are the future steps of IoT-based BAS toward sustainable building practices and smart city initiatives?

The present work aims 1) To conduct a comprehensive literature review and analysis to identify recent advancements in IoT-based BAS technologies and synthesize findings from current research studies. 2) To explore the approaches of IoT-based BAS to improve energy efficiency, occupant comfort, and CO_2 reduction in buildings. 3) To technically analyze interoperability, security, and scalability challenges in implementing IoT-based BAS, proposing potential solutions and best practices to address these challenges. 4) To provide suggestions for future research in IoT-based BAS that contributes to sustainable building practices and smart city initiatives, integrating insights to develop actionable recommendations and guidelines.

The summary of this work's contributions is as follows: 1) This research extensively evaluates IoT-BAS integration in buildings for saving energy, improving user comfort, and reducing emissions. 2) Addresses interoperability, security, and scalability challenges of IoT-BAS through standardization initiatives, cybersecurity precautions, and scaling strategies. 3) Creates a research framework connecting theoretical aspects with real-world applications, assuring the implementation of the proposed solutions in commercial buildings, smart buildings, and renovated infrastructures. 4) Provides valuable insights for building engineers, facility managers, policymakers, and industry professionals supporting strategies for sustainable building practice and energy management.

The format of the paper is as described below: The research methodology is explained in section 2. Section 3 details the traditional BAS. Section 4 explains IoT technologies for BAS. Section 5 describes IoT applications in smart buildings. Section 6 examines the role of IoT-based BAS for energy efficiency, occupant comfort, and emission reduction. Research gaps and recommendations for future work are discussed in Section 7. The final Section presents the conclusion.

2. Research methodology

A systematic review addresses a specific research issue by assembling all practical evidence that meets predetermined eligibility requirements. It uses precise, systematic methods to minimize bias, generating reliable data that helps to arrive at evaluations and conclusions [24]. Additionally, approaches could be employed to determine which sample features or study-level factors influence the subject matter under examination [25]. The several phases in the research approach are identification, screening, and eligibility, including assessment of sources, structured evaluation, and synthesis.

This study uses structured evaluation as a numerical tool to map and visualize the vital aspects of IoT-based BAS methodically. Compared to narrative reviews, which provide broad and unstructured discussions, structural evaluation categorizes the IoT-BAS components systematically, ensuring clarity and integrity. Unlike thematic analysis, which concentrates on recurring themes without directly linking problems to solutions, this method identifies changes and provides targeted solutions, making the research findings more feasible. Furthermore, reviews using statistical meta-analysis provide quantitative insights but often lack contextual depth and practical usability, whereas this approach balances the technical analysis with the real-time application. Through organizing key concepts, preserving logical flow, and linking theory with practice, structural evaluation is a superior, more comprehensive, solution-driven, and adaptable method than other techniques. The methodical survey process used in this work is explained in the PRISMA(Preferred Reporting Items for Systematic Reviews and Meta-Analyses) chart shown in Fig. 1.

2.1. Sorting of literature (levels 1–4)

The Web of Science (WOS) and Google Scholar were chosen as the main databases for this study as they contain expert-assessed, categorized publications highly valued by academics. To further investigate the IoT-BAS area and its transdisciplinary themes, other sources such as ELSEVIER, IEEE Xplore, Springer, ACM Digital Library, ResearchGate, and Academia were used. The search query contained keywords like "Internet of Things," "Smart buildings," "Building automation," "Energy efficiency," and "Sustainability" to guarantee a comprehensive search. Table 1 provides all the keywords relevant to IoT-BAS in this study.

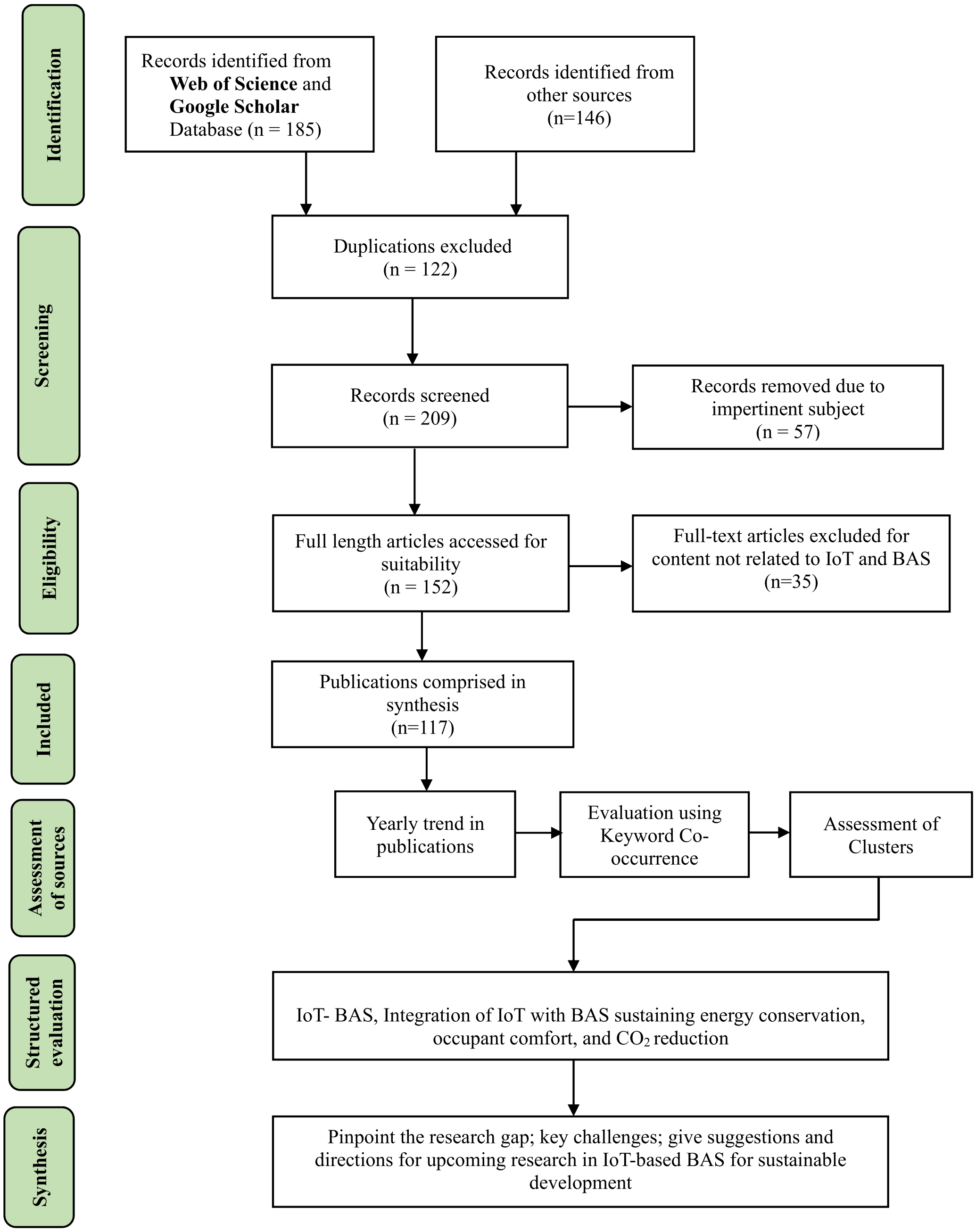

Fig. 1. PRISMA chart used in the methodical survey process.

To obtain superior publications, the current research adhered to the following selection standards: (i) articles or review papers; (ii) publication year spanning from 2010 to 2023; (iii) full text about IoT and BAS; (iv) removal of irrelevant and redundant content. Based on the selection standards 331 publications are sorted out. To further align the publications with this study the following exclusion criteria are used: i) studies focusing on general IoT applications without a direct connection to BAS. ii) research works on standalone smart home automation, smart grids, or unrelated IoT fields iii) papers without a detailed technical analysis of interoperability, scalability, and security challenges in IoT iv) studies with incomplete methodologies, lack of empirical data, or unsupported claims. Using the above exclusion criteria 214 publications are eliminated. Table 2 shows the dispensation of the remaining 117 articles scrutinized from the journals/sources based on the stated selection standards and exclusion criteria.

2.2. Citation assay (level 5)

2.2.1. The analysis of publications from (2010–2023) used in this research

The number of publications referred from 2010 to 2023 in the IoT-BAS field closely relevant to this study is shown in Fig. 2. Before 2010, research on this topic was limited due to outdated standards and technologies. From 2010 to 2013, there was a gradual rise in this research topic, due to increased interest in automation and the advent of IoT technology. From 2013 to 2023 there was a substantial surge in research interest and engagement with IoT-based BAS topics which continues to increase in the future. The chosen period (2010–2023) assures a thorough examination of recent and significant advancements in this field. Additionally, it analyzes the growing recognition of the importance and relevance of IoT technologies in building automation systems and their impact on various domains such as energy efficiency, sustainability, and smart building management.

2.2.2. Co-occurrence evaluation of keywords

This research work used the Co-occurrence evaluation of keywords to determine the main areas of concern that comprise the IoT-based BAS for sustainable development. It involves analyzing the frequency and patterns of occurrence of keywords related to these topics within the literature. The co-occurrence network consists of 92 unique keywords as shown in Fig. 3. These keywords are grouped into 9 distinct clusters, suggesting common research themes or topics within the literature. There are a total of 434 links between the keywords, indicating the frequency of co-occurrence or association between them. The total link strength, which measures the overall strength of connections between keywords, is calculated to be 1388. Each of the 92 keywords has no duplications and its frequency of repetition is three or greater than three. Moreover, the size of the node corresponds to its rate of occurrence.

The importance of 32 keywords positioned by their values of instances in the context of smart buildings for sustainable development, particularly within the realm of IoT-based BAS is given in Table 3. The overall link strength serves as an indicator of the attention these keywords garnered over time. A higher link strength suggests greater interconnectedness with various study themes. The terms "Smart buildings," "Internet of things," "Building Automation," “Sensors”, “Actuators”, “HVAC”, “Lighting”, “Control”, "Energy efficiency" “Sustainability” and “Occupant comfort” are some of the important keywords demonstrating their importance in the IoT-BAS field.

2.2.3. Examination of clusters

To determine the key areas and disclose the conceptual framework of the IoT-based BAS for sustainable development, this study uses cluster evaluation. The VOS viewer software groups the nodes (keywords), as seen in Fig. 3, into nine clusters using the following color schemes: purple, orange, yellow, pink, red, sky blue, green, dark blue, and brown. Keywords like "Smart buildings", "Internet of Things", "Smart cities", "Cloud computing" and "Big data analytics" are specifically found in purple cluster 1; in orange cluster 2, "Building Automation" "HVAC", "Energy management", "Smart systems" and "Control system"; in yellow cluster 3, "Machine learning", "Ventilation", "Lighting", "Control" and "Cyber-physical systems"; in pink cluster 4, "Buildings", "Sensors", "sustainability," "Planning", and "Knowledge based systems"; in red cluster 5, "Energy efficiency", "Energy saving ", "Energy", "Occupancy", "Occupant comfort" and "Deep learning"; in Sky blue cluster 6, "Actuators", "Architecture", "semantics", "context" and "Ontologies"; green cluster 7, "Computer architecture", "Protocols", "Sensing", "Security and privacy", "Ambient intelligence" and "Enabling technologies"; in dark blue cluster 8, "Building Automation System", "Thermal Comfort", "Artificial Intelligence" and "Multi objective optimization"; in brown cluster 9, "Wireless Sensor Networks", "Internet", "Monitoring" and "Building management system". In general, the main fields of study determined are: 1) Traditional BAS 2) IoT technologies in BAS 3) IoT applications in smart buildings 4) Role of IoT-BAS for energy efficiency, occupant comfort, and sustainability 5) Challenges in IoT-BAS integration and offering solutions. The above research domains provide a structure for the ensuing in-depth examination.

Table 1
Keywords to facilitate comprehensive examination of literature.

Search strings used
(“Smart buildings” OR “Internet of Things” OR “Building automation” OR Building Automation Systems” OR “Building energy management systems” OR “Building Information Systems” OR “Building Automation and control systems” OR “sensors” “Sustainable building” OR “Sustainable development” OR “High-performance building” OR “Energy efficient buildings”) AND (“Occupant comfort” OR “Thermal comfort” OR “Carbon reduction” OR “Heating, ventilation, and Air Conditioning systems” OR “Optimization” OR “Energy efficiency” OR “Energy management” OR “Energy saving” OR “Interoperability” OR “Security” OR “Scalability”)

Table 2
Details of articles scrutinized in this study from the journals/sources.

S. NO	Name of Journals/Sources	No.of articles searched	No.of articles referred for this study	Contributing percentage (%)
1	Energy and Buildings	60	22	18.80
2	Building and Environment	25	16	13.68
3	Automation in Construction	20	14	11.97
4	Journal of Building Engineering	16	9	7.69
5	Energy and Built Environment	14	7	5.98
6	Renewable and Sustainable Energy Reviews	10	6	5.13
7	Sustainable Cities and Society	9	5	4.27
8	Energy Strategy Reviews	5	2	1.71
9	Applied Energy	7	4	3.42
10	Journal of Cleaner Production	10	5	4.27
11	Future Generation Computer Systems	6	3	2.56
12	Advanced Engineering Informatics	5	2	1.71
13	Computer Communications	6	2	1.71
14	Computer Standards and Interfaces	5	1	0.85
15	Journal of Network and Computer Applications	4	1	0.85
16	Computer Networks	3	1	0.85
17	Journal of Computer and System Sciences	2	1	0.85
18	IEEE Internet of Things Journal	10	4	3.42
19	IEEE Sensors Journal	5	3	2.56
20	IEEE Transactions on Industrial Electronics	3	1	0.85
21	ACM Digital Library	40	3	2.56
22	Research Gate	30	3	2.56
23	Academia.edu	36	2	1.71
	Total	**331**	**117**	**100**

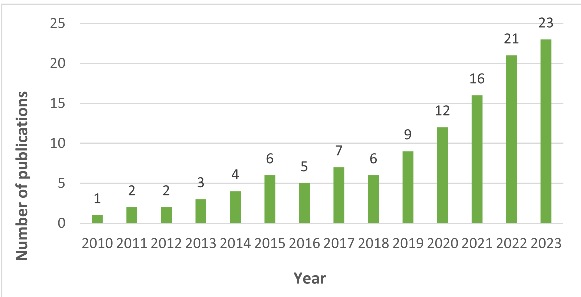

Fig. 2. Yearly distribution of the number of publications from 2010 to 2023 considered in this study.

2.3. *Structured evaluation (level 6)*

This study performs a systematic literature review after a structured evaluation to offer thorough insights into the IoT-BAS research topic. The structured evaluation reveals five domains as important areas of research attention. These fields were then divided into two groups: IoT-BAS applications and IoT-BAS integration. The first category details how IoT improves occupant comfort, reduces CO_2 emissions, and supports the BAS. The second category discusses the challenges in the IoT-BAS integration and strategies to attain sustained building solutions. Before exploring IoT-BAS, it is essential to understand the fundamentals of traditional BAS first. The following section provides an overview of conventional BAS, its architecture, control mechanisms, and drawbacks that necessitate the shift toward IoT-based solutions.

3. Traditional BAS

BAS is a network installed within buildings to regulate and inspect essential services such as air conditioning, heating, ventilation, lighting, shading, life safety, security alarms, and various other systems. It is designed to automate tasks within technologically advanced environments, orchestrating various devices with mechanical and electrical connections dispersed through underlying control networks [26]. Actuators, sensors, and hardware modules make up a BAS configuration. Actuators are physical devices like shutters for windows or roof lights that respond to signals by shutting down networks or changing the strength of electrical loads. Sensors are tools that transform the physical world into a signal with measurable content. Hardware modules' I/O ports are connected with actuators and sensors that generate electrical signals in response to orders for digital output and extract readings from signal inputs [27]. The exchange of information between sensors, actuators, controllers, and other devices with the central management system is done through commonly used communication protocols such as BACnet, Modbus, Zigbee, Wi-Fi, and Ethernet [28].

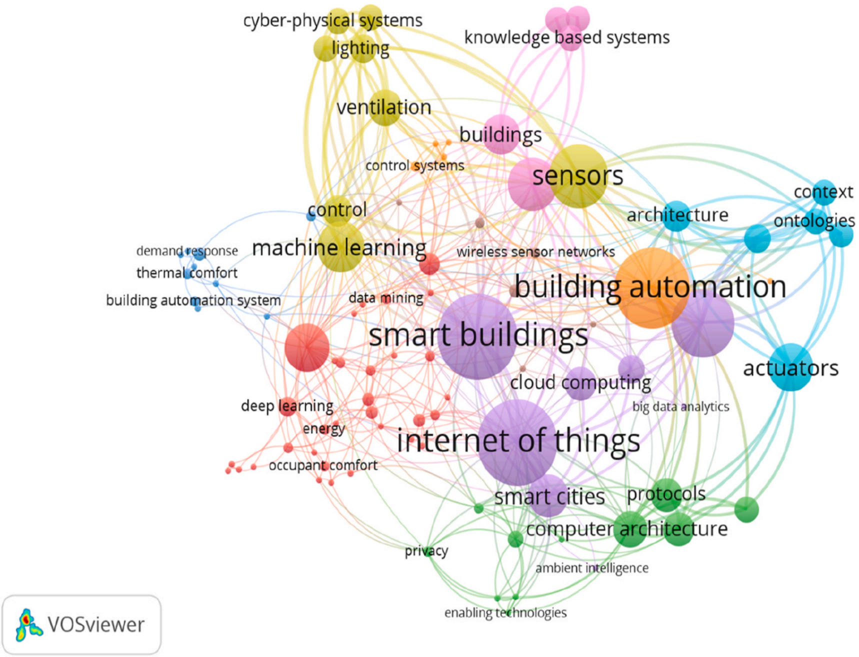

Fig. 3. Co-occurrence network with keywords.

Table 3
The 32 most often occurring keywords.

Position	Keywords	Instances	Total Link Strength
1	Smart buildings	30	181
2	Sensors	22	162
3	IoT	23	152
4	Building automation	28	133
5	Internet of Things	30	130
6	Actuators	16	112
7	Automation	18	105
8	Machine learning	17	93
9	HVAC	12	92
10	Smart cities	14	89
11	Control	10	87
12	Lighting	9	85
13	Design automation	8	80
14	Hardware	8	80
15	Cyber-physical systems	8	80
16	Cloud computing	11	79
17	Smart homes	9	77
18	Architecture	10	74
19	Computer Architecture	12	67
20	Ontologies	8	64
21	Semantic technologies	8	64
22	Intelligent sensors	11	62
23	Multi-heterogeneous technology integration	8	48
24	Sustainability	13	40
25	Energy efficiency	16	25
26	Planning	8	24
27	Energy consumption	7	16
28	Optimization	4	11
29	Occupant comfort	4	9
30	Energy Management	3	8
31	Energy	3	7
32	Energy saving	3	6

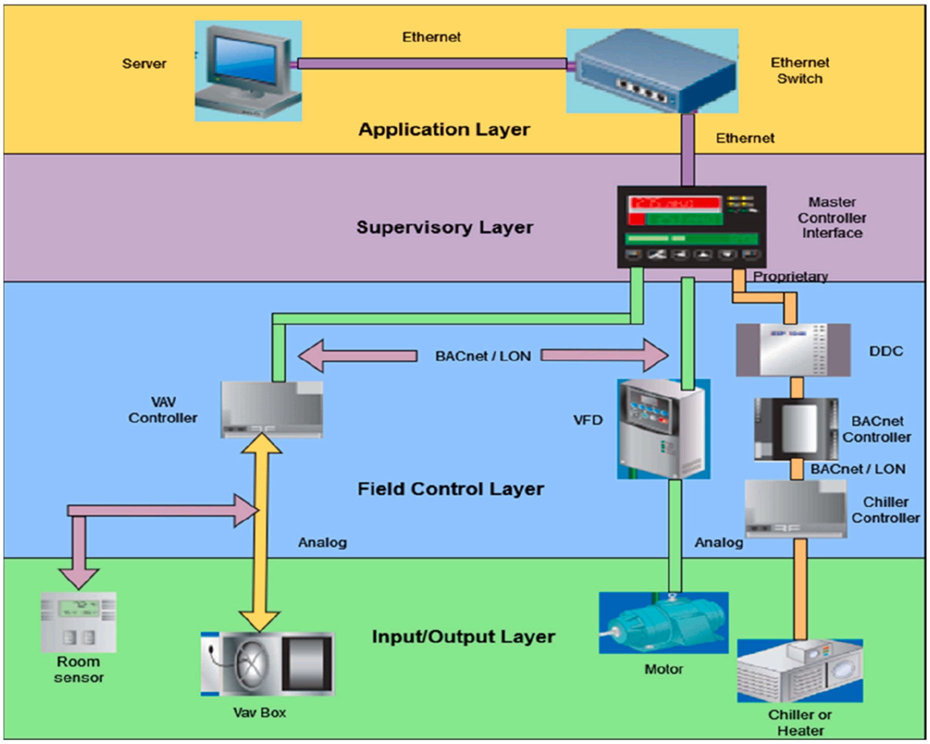

Fig. 4. Architecture of BAS

The architecture of BAS is shown in Fig. 4. The field level consists of all the equipment that physically operates or detects building functions. Connecting actuators, sensors, and other field-level devices to an automation-level PLC (Programmable Logic Controller) or RTU (Remote Terminal Unit) is the primary function of the field network. The four ways of physically connecting the two layers are power lines, hardwired, bus systems, and wireless. All sophisticated controllers that manage and direct the real-time field-level devices are part of the automation level. In BAS, the main network links the management and automation levels. A building's conventional

Table 4
Articles related to BAS.

References	Focus	Inference
Joao et al. [30] (2010)	Integration of BAS Demand-Side Management with the building's energy production system	• BAS combines Demand-Side Management with renewable energy production systems. • Ensures a balance between demand and production while meeting sustainability and environmental values.
Bhatt et al. [31] (2015)	Development of operational pilot models for home security and extensive building automation, using economical designs.	• BAS provides intelligent data reporting, robust security, and a user-friendly interface.
Domingues et al. [8] (2016)	The problem of heterogeneity faced by BA.	• Systematizes BA concepts and requirements based on established standards. • No existing approaches can fully overcome this heterogeneity problem.
Schmidt et al. [32] (2017)	Developing advanced predictive building control strategies to enhance energy efficiency in legacy and modernized buildings	• Integrates the existing equipment into a forecasting cyber-physical system powered by data. • Combines general model-based design techniques and data mining using industry-wide standards.
Aparicio-Ruiz et al. [33] (2018)	Improving energy efficiency while maintaining user comfort in the building's BAS.	• An experimental adaptive control algorithm is proposed for a workplace without extra expenses or specialized hardware. • Determines the relation between occupant comfort and energy efficiency.
O'Grady et al. [34] (2021)	To identify research trends and patterns in BAS by conducting a structured literature survey and meta-study.	• Emphasizes integrative feedback loops that increase occupant acceptance and BAS adoption.
Qiang et al. [35] (2023)	To reduce energy loss in the building industry and to emphasize the importance of BAS for improving energy efficiency in GB.	• Suggestion of five techniques for integrating BAS-GB to increase energy saving. • Identification of four challenges uncertainties, long-term prediction, aspirations for sustainability, security, and privacy for BAS and GB integration.

Local Area Network (LAN) and the primary network either coexist or divided. A network switch is used in LAN to link several nodes and enable communication between them. The automation level and the primary network are connected by secondary networks. The management level includes all gadgets that oversee and keep an eye on the building automation system, communicate with staff, and use the internet [29]. A summary of the articles related to BAS is given in Table 4.

Table 4 collectively examines various aspects of BAS, including their integration with energy production systems for sustainability, development of cost-effective home security models, addressing heterogeneity in Building Automation (BA), enhancing energy efficiency through predictive control, balancing energy efficiency with occupant comfort, identifying research trends, and proposing methods for integrating BAS with green buildings to reduce energy wastage. The drawbacks of traditional BAS are given below.

- Often relies on proprietary hardware and protocols, making it difficult to scale and expand as building requirements evolve.
- Typically, rigid and inflexible, making it challenging to adapt to changing building needs or integrate with emerging technologies.
- The initial installation cost can be high, particularly for smaller buildings or retrofits.
- Provides basic monitoring and control functionalities, offering limited insights into building performance and occupant behavior.
- Vendor-specific and restrict building owners to a single supplier, limiting choice, interoperability, and innovation.
- The centralized approach can create single points of failure, scalability bottlenecks, and performance limitations.
- Lacks native support for modern communication protocols or integration interfaces, making it difficult to connect with external systems.
- Susceptible to cybersecurity threats due to outdated or inadequate security measures.

Although traditional BAS plays an essential role in automating building operations due to the above drawbacks, it struggles to respond dynamically to real-time occupancy changes, environmental changes, and energy demand fluctuations. So, it is gradually replaced or upgraded with IoT-driven solutions. The transition from conventional BAS to IoT-based building automation represents a significant change in achieving energy-efficient, occupant-centric, and sustainable buildings.

4. IoT technologies for BAS

IoT is a network of linked devices with built-in software, sensors, and actuators to gather, share, and analyze data independently. The IoT components are shown in Fig. 5. At the heart of IoT are the sensors that collect information like humidity, temperature, motion, and sound from the surrounding environment. The gathered data is sent to centralized platforms or cloud-based systems for refining, analyzing, and obtaining understandable and actionable information [36].

The IoT architecture given in Fig. 6 is a framework that enables the seamless integration and functioning of connected devices. The architecture typically contains several layers, each in charge of particular functions. The sensing layer consists of tangible objects with sensors and actuators for communicating with the real world. Sensors gather environment data, while actuators allow devices to respond to commands based on received instructions. The network layer enables the connectivity of IoT devices, enabling the transfer of data over various network protocols and technologies layer comprises cellular networks (3G, 4G, and 5G), Ethernet, Wi-Fi, Bluetooth, Zigbee, and LoRaWAN (Long Range Wide Area Network), among other wired and wireless communication technologies. Network protocols like CoAP (Constrained Application Protocol), HTTP (Hypertext Transfer Protocol), and MQTT (Message Queuing Telemetry Transport) govern the data exchange between devices and the cloud or edge servers [37]. The data-handling layer processes, stores, and analyzes the data gathered from IoT devices. Data collection occurs at different levels, including the edge, fog, and cloud.

The application layer encompasses the user-facing applications, services, and interfaces that interact with IoT devices and data. These applications may include web-based dashboards, mobile apps, APIs (Application Programming Interfaces), and enterprise software platforms. End-users, businesses, or organizations utilize these applications to monitor and control IoT devices, visualize data insights, set alerts and notifications, and automate workflows [38]. The findings of the works related to IoT-based BAS are given in Table 5.

Table 5 explores how IoT enhances building management and automation systems through simultaneous surveillance and management of several systems like lighting, energy, and structural health. They highlight the integration of smart sensors, meters, and actuators for efficient energy management and virtual sensing. The findings emphasize the benefits of IoT in optimizing building operations, improving visualization, and aiding decision-making for better facility management and thermal comfort.

The difference between traditional and IoT-based BAS is shown in Fig. 7. An IoT-enabled BAS offers the following benefits.

- Social approach and the occupants are key considerations while making decisions.

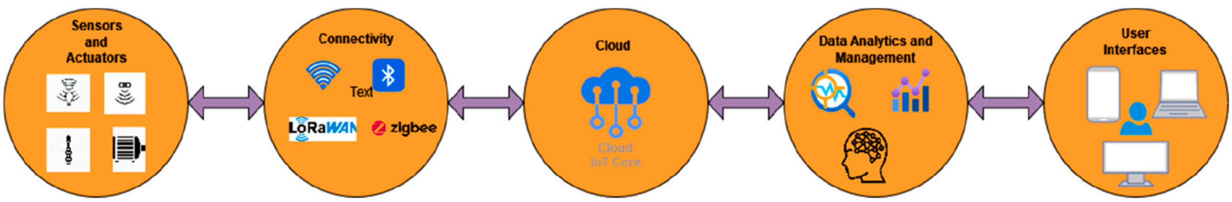

Fig. 5. Vital IoT components.

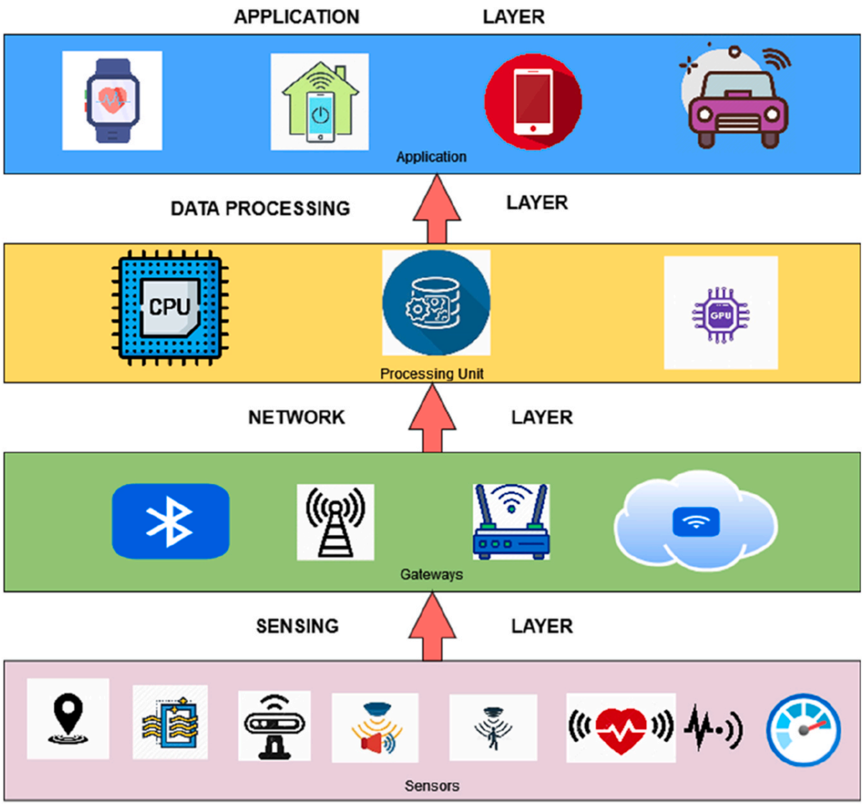

Fig. 6. Architecture of IoT.

- Better tracking of behaviors and occupant location awareness.
- The ability to gather energy, which minimizes the requirement for interaction.
- Low-cost sensors that monitor and analyze less critical elements without the need for financial explanation;
- Networks that are intrinsically supported by wireless and low bandwidth.
- Aspects of consumer behavior, wellness, and lifestyle are essential in IoT-BAS.

IoT technologies reform the conventional BAS into intelligent, adaptive, and efficient systems. Through smart sensors, edge computing, cloud analytics, and cybersecurity frameworks, the IoT advances the BAS towards optimized energy, comfort, and sustainability in buildings. However, the true impact of these advancements is realized through their practical implementation in smart buildings. The following section explores the key IoT applications in smart buildings.

5. IoT applications in smart buildings

IoT applications in smart buildings shown in Fig. 8 include a wide range of functionalities, from environmental monitoring and energy management to security, occupancy tracking, and predictive maintenance [48]. Among the IoT applications in smart buildings, environmental monitoring is very crucial. Sensors deployed in the building gather data on many aspects, including humidity, temperature, air quality, and lighting levels. This real-time data collection through IoT enables HVAC optimization that minimizes energy consumption while maintaining optimal indoor environmental conditions for occupants [49].

Energy management in smart buildings is highly improved by IoT technology. Smart meters and energy monitoring devices track energy usage patterns, enabling building operators to recognize opportunities for real-time energy conservation and demand response. By analyzing this data, smart buildings can implement energy-saving strategies such as load balancing, peak shaving, and scheduling energy-intensive tasks to reduce utility costs and environmental impact [50]. IoT applications also enhance security in smart buildings by deploying intrusion detection sensors, access control systems, and surveillance cameras. These devices are connected to centralized monitoring systems that provide real-time alerts and notifications in the event of security breaches or unauthorized access, enabling rapid response and mitigation of security threats [51].

Occupancy tracking is another valuable IoT application in smart buildings, allowing building operators to monitor occupancy levels instantly in different areas of the building. This information is utilized to optimize space utilization, improve building layout and design, and enhance overall operational efficiency. Furthermore, predictive maintenance is facilitated by IoT sensors that continuously monitor the health and performance of building systems and equipment. By detecting anomalies and early signs of malfunction, these

Table 5
Articles related to IoT-based BAS.

References	Methods	Findings
Minoli et al. [39] 2017	IoT-based BMS platforms to monitor and control a building's mechanical and electrical types of equipment.	• BIMs incorporate data from IoT-based sensors, encompassing energy, lighting, and surveillance systems. • Perform a variety of tasks to monitor and modulate energy in real time.
Tushar et al. [40] (2018)	IoT-based BMS for energy consumption monitoring and management.	• The IoT offers opportunities to integrate intelligence into BMS by integrating sensors, smart meters, and actuators seamlessly.
Verma et al. [41] (2019)	Reviews IoT infrastructure, IoT communication systems, and sensors used for sensing, and controlling in buildings.	• Sensing and managing the IoT framework allows cloud clients to leverage remote sensing. • Uses Long-range digital wireless data communication (LoRa).
Misra et al. [42] (2020)	A real-time IoT platform for structural health monitoring using sensors and network connectivity to detect the health of structures and transmit the data remotely to any part of the world.	• It uses cloud and mobile app-based monitoring. • Monitors damage in concrete structures and uploads data to a cloud server. • IoT links various devices to the internet and helps in smart structural health monitoring.
Quinn et al. [43] (2020)	Integrates IoT sensor data to Facility Management Building Information Modeling (FM- BIM)	• The complex temporal sequence information can be represented and plotted onto the FM-BIM. • FM BIMs allow for cloud-hosted building management.
Valinejadshoubi et al. [44] (2021)	Integrates IoT sensor-based warning system for building thermal comfort monitoring into BIM models	• Provides a robust instrument for authentic data gathering, processing, and display. • Enables smart tracking of building temperature conditions • Helps decision-makers to act more quickly and effectively.
Li & Wang [45] (2022)	An ideal control strategy that is fully distributed for multi-zone dedicated outdoor air systems in building automation networks enabled by the IoT.	• Provides the best optimization efficiency, the least computational complexity, and superior robustness. • The IoT-enabled intelligent sensors with restricted capacity will function with optimal control performance.
Ruiz-Zafra et al. [46] (2022)	Incorporating IoT into the initial phases of building design using Industry Foundation Classes Plus (IFC+) to convert software requirements for smart-built environments	• IoT technologies in Building Information Modeling (BIM) enhance facility management and enable smart environments. • Many devices deployed are not accessible until after the construction is completed
Li et al. [47] (2023)	An ideal control strategy for air conditioning systems that is fully distributed and robust	• Ensures ideal performance control in typical and link failure scenarios, with minimal computational complexity and high optimization efficiency.

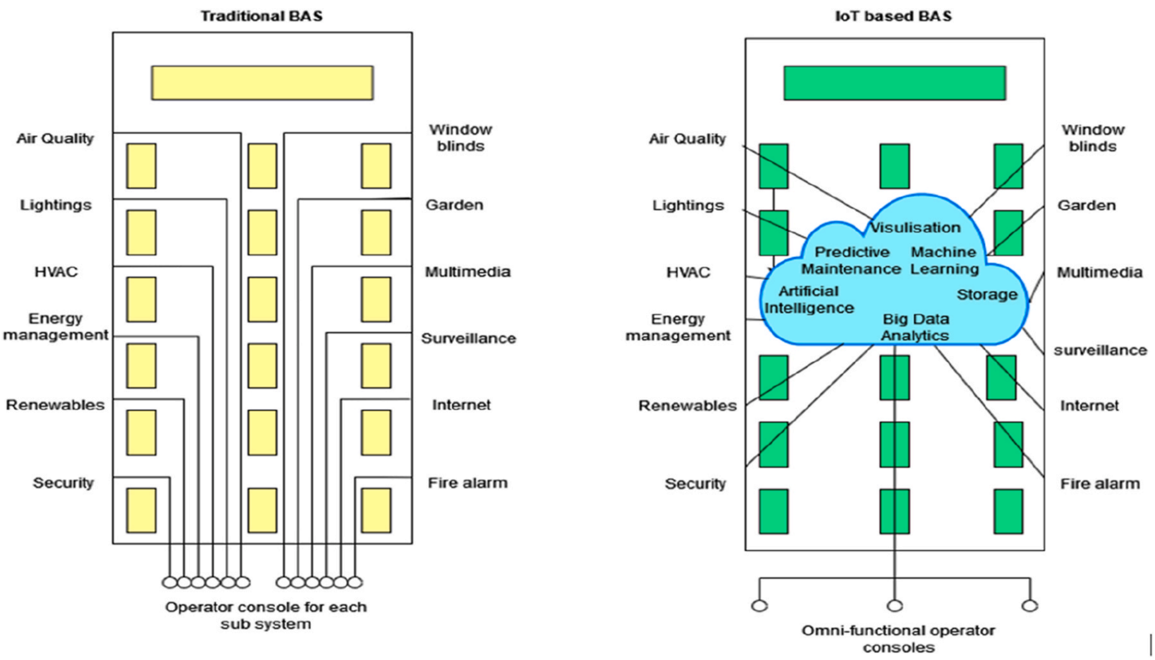

Fig. 7. Traditional BAS vs IoT-based BAS.

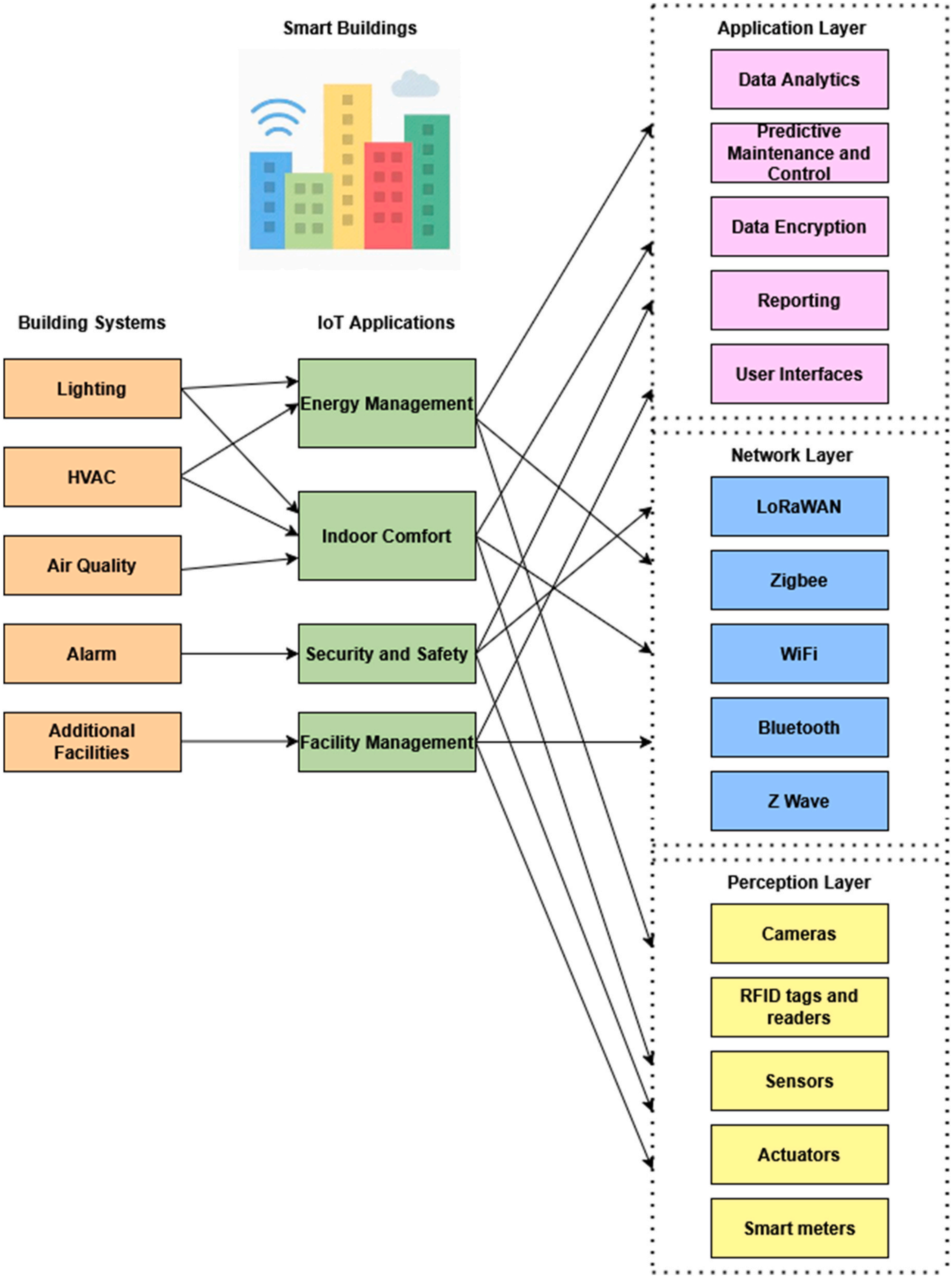

Fig. 8. IoT applications in smart buildings.

Table 6
Articles related to IoT technologies in smart buildings.

References	IoT Technologies	Applications
Hernández-Ramos et al. [53] (2015)	ARM-compliant IoT security framework for smart buildings, integrating contextual data for building management and security behavior	• Applied on a City Explorer platform and verified in a reference smart building • Achieves energy savings, service discovery, and authorization.
Shah & Mishra [54] (2016)	A personalized IoT-capable platform in smart buildings for wireless detection and supervision	• Monitors relative humidity, temperature, and light within the framework of automated buildings. • Provides comfort, security, and energy savings by monitoring daily energy consumption
Lilis et al. [55] (2017)	IoT in intelligent building development, focusing on occupant-centered approaches and power grid services	• Provides sophisticated building management systems that combine the strength of current automation technologies with new developments.
Plageras et al. [56] (2018)	Cloud computing, IoT, and big data are combined to explore new systems.	• Data collected by a cloud server from each sensor, can be easily governed through a remote system on an IoT network • Leads to a low-energy and smart eco-friendly building.
Jia et al. [57] (2019)	IoT and its network of connected functional entities in different aspects of a building equiping all objects.	• The smart environment provided by IoT enables all objects to comprehend their surroundings and engage in fruitful discussions with persons. • Help individuals to make decisions.
Metallidou et al. [58] (2020)	Integrates IoT technology into distributed energy systems.	• Reduces time-consuming processes and stores the energy performance data of each building on a cloud platform. • Achieves energy efficiency, reduce waste, and improve environmental conditions.
Arun Kumar et al. [59] (2021)	IoT-based smart building architecture is proposed using CoAP and Datagram Transport Layer Security (DTLS)	• Integration of DTLS with Secure Hash Algoritthm-256 improves security. • Energy consumption is reduced by 30.86 % with CoAP in smart buildings, less than the Message Queuing Telemetry Transport case. •
Tarun Kumar et al. [60] (2022)	Wireless Sensing Systems based on IoT are deployed in smart buildings	• Building Energy Model developed with the EnergyPlus™ dynamic simulator in DesignBuilder V7 calculates the building's active energy. • The custom-built CO_2 sensor gathers instant user data to integrate into the model to reduce energy consumption and environmental impacts.
Krishnan et al. [61] (2023)	IoT sensors in smart buildings analyze various prime factors that help to enhance energy savings.	• Abnormalities such as power usage outliers are detected and managed either automatically or manually. • Improves sustainable development in terms of smart building energy use.

sensors enable proactive maintenance actions, minimizing downtime, extending equipment lifespan, and reducing maintenance costs [52]. The applications of IoT technologies in smart buildings are given in Table 6.

Table 6 details various IoT technologies and their applications in smart buildings. These technologies include ARM-compliant IoT security frameworks, customized wireless sensing and monitoring platforms, and integration with big data and cloud computing for sensor data management. Applications range from enhancing energy efficiency, security, and comfort to improving environmental conditions and facilitating smart decision processes. The IoT integration in smart buildings greatly reduces energy consumption by dynamically adjusting the settings based on real-time occupancy and outdoor conditions. It improves advanced building management, real-time data collection and analysis, and the development of secure, energy-efficient, and intelligent building architectures.

The following section analyzes how IoT-based BAS improves energy efficiency and indoor environmental quality and contributes to CO_2 reduction. This section explores the key strategies and technologies that drive these improvements, emphasizing their impact on smart performance and sustainability.

6. Role of IoT-based BAS for energy efficiency, occupant comfort, and emission reduction

The IoT-based BAS allows the creation of smart buildings that can spontaneously adapt to shifting energy requirements, occupancy patterns, and environmental conditions in real time. Utilizing IoT sensors in BAS enables the collection of humidity, temperature, occupancy, and energy consumption data, which in turn helps BAS to make informed decisions and automate control strategies to maximize efficiency and comfort [62,63]. Moreover, IoT-enabled BAS offers flexible and smooth building control, assisting building operators to adapt their systems to meet evolving needs and technologies. With the ability to remotely monitor and control building systems through IoT-connected devices, facility managers can optimize performance, reduce maintenance costs, and extend the lifespan of building assets [64]. Fig. 9 shows the IoT-based BAS towards sustainable development. It plays a vital role in advancing sustainability efforts and minimizing ecological footprint through

- Energy efficiency and conservation
- Improving occupant comfort

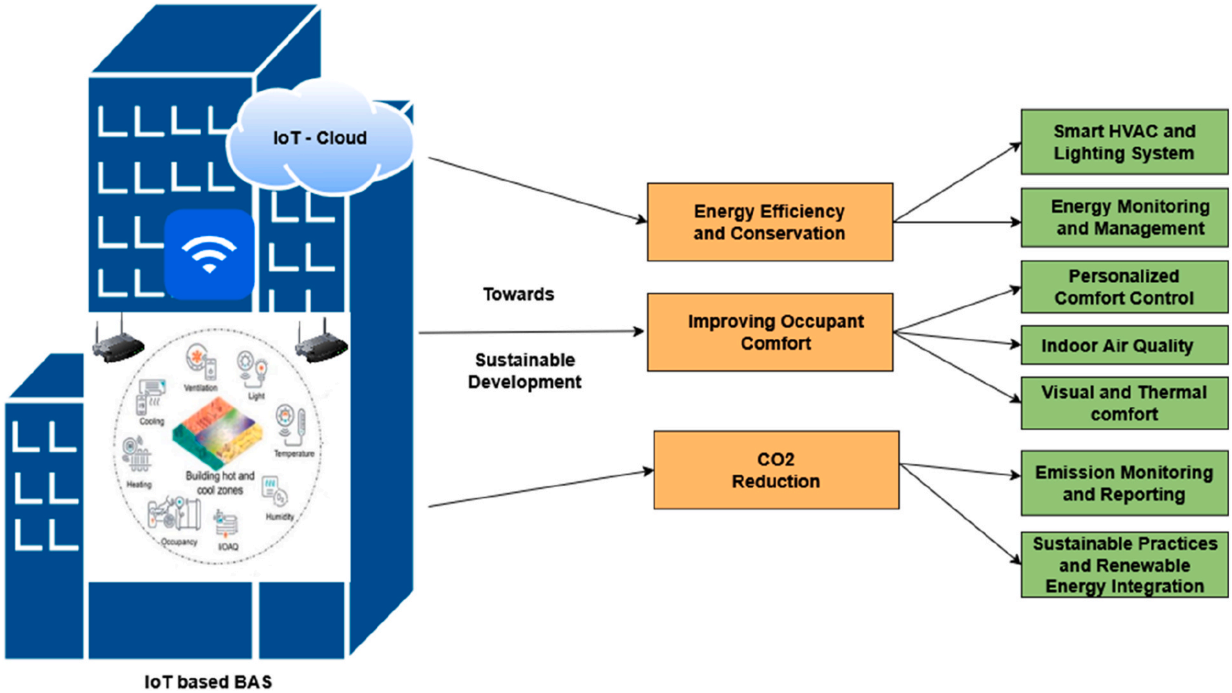

Fig. 9. IoT-based BAS towards sustainable development.

- CO_2 reduction

6.1. Energy conservation through IoT-based BAS

Energy conservation in buildings is crucial and IoT-driven BAS helps in energy conservation by enabling proactive monitoring, intelligent control, and optimization of building systems. By leveraging smart sensors, cloud computing, and predictive analytics it reduces energy waste and enhances operational efficiency in modern buildings. The indoor environment data collection by the IoT sensors helps BAS analyze energy usage patterns and identify energy inefficiencies [65]. It enables

Table 7
Articles related to smart HVAC and lighting systems.

References	Building System	Method	Inference
Png et al. [69] (2019) Figueiredo et al. (2021) [70]	HVAC HVAC	Energy minimization in commercial building HVAC systems using Smart-Token Based Scheduling Algorithm Smart home IoT systems with a flexible hybrid wireless network architecture for HVAC control and regulation.	• The model encapsulates hardware, software, networking, and their interactions, addressing challenges in scalability and low-cost resource constraints. • The model uses occupant thermal perception, decentralized control, and recurrent zone heat mapping identification prediction. • Integrates IEEE 802.11/Wi-Fi and Bluetooth Low Energy to accommodate various sensors and actuators • The system was less expensive and uses Raspberry Pi for smart HVAC control.
Liang et al. [71] (2023)	HVAC	IoT-based intelligent energy management system (EMS)	• Optimizes HVAC scheduling, balancing user comfort. • Additionally, it significantly improves the remaining energy of the battery.
Weitao Xu et al. [72] (2019)	Lighting	Emergency light-based smart building solution, built on existing building facilities.	• The system covers the entire building with a single gateway using the LoRa mesh network. • Long-term resilience to changes in the environment, node failure, and gateway failure
Lee et al. [73] (2022)	Lighting	A Passive Infrared Sensor (PIR), Infrared (IR) sensor, human movement sensor and counter-based IoT technology	• Lighting systems using smart LED are affordable, simple to fix, and energy-efficient. • Their parameters can be adjusted promptly using microcontrollers through the Internet and IoT.

- Smart HVAC and lighting systems
- Energy monitoring and management

6.1.1. *Smart HVAC and lighting systems*

IoT sensors embedded with HVAC and lighting systems collect temperature, humidity, occupancy, and light level data, providing real-time insights into building conditions. BAS uses this data to dynamically adjust the HVAC settings and lighting levels based on occupancy preferences, patterns, and environmental conditions, minimizing energy consumption while maintaining user satisfaction [66]. It facilitates predictive maintenance for HVAC and lighting equipment by continuously monitoring performance metrics and detecting anomalies or signs of wear and tear. By identifying potential issues early on, BAS enables proactive maintenance activities, preventing costly breakdowns and ensuring the efficient operation of HVAC and lighting systems [67]. It employs adaptive control strategies to optimize HVAC and lighting operations in response to changing conditions. It adjusts HVAC setpoints and fan speeds based on occupancy levels, temperature gradients, and outdoor weather conditions, ensuring efficient energy use while minimizing energy waste [68]. The inferences from the works related to smart HVAC and lighting systems are summarized in Table 7.

Table 7 highlights IoT-based methods to enhance energy efficiency and control in HVAC and lighting systems within buildings. In HVAC systems, smart scheduling algorithms and flexible hybrid wireless networks optimize energy use and user comfort using Bluetooth, Wi-Fi, and intelligent energy management systems. For lighting, IoT solutions involve emergency light systems using LoRa networks and smart LED lighting with IR sensors, offering energy savings, easy installation, and resilience to environmental changes and system failures. These systems can also be customized to individual user preferences, improving occupant well-being while maximizing energy savings. By integrating smart HVAC and lighting into a unified IoT-driven BAS, buildings can accomplish seamless automation, self-learning optimization, and interoperability, transforming them into highly efficient, responsive, and sustainable environments that align with modern smart city initiatives.

6.1.2. *Energy monitoring and management*

IoT-based BAS enables building owners and operators to track, analyze, and optimize energy usage effectively. With IoT sensors deployed throughout the building, BAS continuously accumulates current energy usage data from various systems and devices, including HVAC, lighting, appliances, and renewable energy sources [74]. This data is aggregated, processed, and visualized through centralized dashboards or energy management software, providing stakeholders with valuable insights into energy usage patterns, trends, and anomalies. It facilitates energy management through remote monitoring and control capabilities, allowing building managers to track energy performance metrics, receive alerts for abnormal energy usage, and implement corrective actions in real time [75]. By remotely accessing BAS interfaces or mobile applications, facility managers can adjust equipment settings, schedule maintenance tasks, or implement energy-saving measures from anywhere, at any time, optimizing energy efficiency and reducing

Table 8
Articles allied to monitoring energy and its management.

References	Focus	Method	Appliances type	Benefits
Pawar & Vittal K [77] (2019)	An IoT-integrated advanced smart energy management (SEM) in the next-generation grid.	*SEM Gateway* - Decisive algorithm *Smart Socket Module* - Cost Optimization Algorithm	Light, Fan, and Laptop	• Visualization of the daily and monthly power consumption data of appliances using IoT. • Its reliable ZigBee connectivity enables data analytics and storage for home area networks.
Mudaliar & Sivakumar [78] (2020)	IoT-based real-time energy monitoring system using Raspberry Pi	Node.js, Raspberry Pi gathers electrical parameters from the industry's current energy	Electrical and mechanical equipment	• Diverse electrical characteristics such as current, voltage, power, frequency, energy, power factor, etc. are displayed using Raspberry Pi in Grafana. • Helpful in understanding the company's daily energy patterns that are crucial for undertaking future energy conservation measures.
Saleem et al. [79] (2021)	Creation, integration, and use of an IoT-based SEMS	It gathers and sends the data via IoT communication protocols to the middleware module	HVAC and lights	• Helps in Demand Side Management (DSM) and non-disruptive load monitoring. • It integrates multiple communication protocols and interfaces to work with software-based intelligent solutions for data gathering and analysis.
Imran et al. [80] (2022)	IoT Task Management-Predictive optimization in residential buildings	Deep Neural Networks-based prediction, Particle Swarm Optimization	Heater, Fridge, Air conditioner, Microwave and Dishwasher	• The various appliances' energy information is received through a web-based Energy Management System (EMS). • The energy minimization is achieved through predictive optimization, optimization, prediction, and IoT task management systems.
Almaki et al. [81] (2023)	IoT and its capabilities to address the needs of smart cities.	IoT data centers, Wireless sensors, cloud computing, and communication technologies	Drones, Mobile phones	• Reduce CO_2 emission, minimize power consumption, and enhance the quality of service.

operational costs [76]. The methods, appliances, and benefits from the works allied to monitoring energy and its management are given in Table 8.

Table 8 focuses on IoT-based SEMS and real-time energy monitoring for various appliances in smart grid environments and residential buildings. Methods include using SEM gateways and smart sockets for demand response and cost optimization, Raspberry Pi for gathering and displaying electrical parameters, and IoT communication protocols for data analysis and user access. Benefits include viewing power consumption data, reliable data analytics, non-intrusive load monitoring, predictive optimization, and reduced CO_2 emissions. These methods apply to wide appliances like lights, HVAC, fans, laptops, heaters, fridges, air conditioners, microwaves, dishwashers, drones, and mobile phones, ultimately enhancing energy efficiency, cost savings, and environmental sustainability.

By continuously observing energy consumption patterns, IoT-driven BAS detects peak demands, inefficiencies, and anomalies, enabling immediate corrective measures and long-term optimization strategies. Moreover, it facilitates the transition of buildings from passive energy consumers to intelligent, self-regulating systems that minimize energy wastage and enhance operational efficiency, leading to long-term sustainability.

6.2. *Improving occupant comfort*

IoT-enabled BAS enables occupants to customize environmental settings such as temperature, lighting, and ventilation according to individual preferences. A well-regulated indoor environment is essential for productivity, health, and overall well-being. Through intuitive interfaces or mobile apps, occupants can adjust settings in their indoor workspace or living environment, empowering them to create personalized comfort zones tailored to their needs. It enhances

- Personalized comfort control
- Indoor Air Quality (IAQ)
- Visual and thermal comfort

The strategies and benefits of the work related to personalized comfort control, IAQ, and visual and thermal comfort are summarized in Table 9.

Table 9
Articles related to personalized comfort control, IAQ, and Visual and thermal comfort.

Reference	Focus	Strategies	Benefits
Marques et al. [82] (2019)	IoT-based Indoor Environmental Quality Measuring System.	The IoT architecture for real-time IEQ monitoring using mobile computer software for data processing, consultation, and notifications, along with a hardware accumulation module for data acquisition.	• The online platform helps to exchange information to aid in the identification of health issues • The real-time monitoring of buildings leads to a decrease the healthcare costs and avoids living under high IEQ levels.
Godithi et al. [83] (2019)	IoT-based visual and thermal comfort in personal environmental control	Intelligent light and thermal sensors integrated with natural resources of outdoor air and daylight	• Greatly minimizes energy usage and improves user comfort
Oana Chenaru and Dan Popescu [84] (2020)	IoT-based personalized user comfort management	Gathering information on temperature, humidity, and CO_2 levels using presence sensors and incorporating this information into air conditioning systems for adjusting set points.	• By utilizing and accessing data from the behavior and context modules, the proposed comfort model adjusts to the actions of the occupants.
Alsaleem et al. [85] (2020)	Estimating and managing thermal comfort using IoT framework	The personalized comfort model employs wearable devices to monitor skin temperature and physiological data	• Integrates human input and feedback to ascertain individual comfort levels. • The comfort model based on wearables selects the exact setpoint of the thermostat in comparison with utilizing a normal thermostat set-point.
Sung et al. [86] (2021)	IoT-based IAQ monitoring	The Arduino Uno development board, coupled with the ESP8266 Wi-Fi module, was utilized to devise a convenient air quality monitoring system.	• Efficient fuzzy control and fuzzy rule foundation created for environment variable simulation • Decision reasoning utilized in place of the indoor air quality threshold control.
Kanna et al. [87] (2022)	Indoor thermal comfort using IoT based on user experience	The BIM-IoT model is developed to integrate user-defined thermal preferences through a mobile app, along with data streams from IoT sensors.	• IoT-based system monitoring ensures the proper functioning of the system. • It enhances the system efficiency and reduces optimal temperature deviations.
Bogatu et al. [88] (2023)	Customised thermal comfort model with automated management	The Personal Environmental Control System (PECS) collects thermal preferences, physiological data, and indoor temperature readings from 24 individuals to manage HVAC systems.	• Clothes held more significance and their assessment is essential for improving the comfort model performance. • The forecasting of thermal comfort is appropriate for the functioning of PECS.
Kar et al. [89] (2023)	Intelligent lighting control for occupant visual comfort	Uses intelligent illumination and occupancy sensors	• The smart Android app can be used which enables the occupants to modify their light preferences in their work area.

Table 9 discusses IoT-based systems for improving indoor environmental quality and personalized comfort. Strategies like real-time monitoring, personalized comfort models, intelligent agents, wearable devices, and mobile apps are employed to collect and analyze data on environmental conditions and occupant preferences. Benefits include enhanced occupant comfort, reduced healthcare costs, improved system efficiency, and optimized temperature control based on individual needs and preferences. These systems adapt to user actions, provide real-time feedback, and ensure efficient working of HVAC and air quality systems.

6.2.1. Personalized comfort control

IoT-based BAS allows for precise temperature control tailored to individual preferences. By adjusting lighting settings based on personal preferences, occupants can create optimal lighting conditions for activities such as working, relaxing, or socializing [90]. By integrating occupancy sensors into BAS, temperature, lighting, and ventilation settings are adjusted automatically when occupants enter or leave a room, ensuring comfort and energy efficiency. IoT-based BAS can incorporate feedback mechanisms to gather data on occupant comfort levels and preferences. By analyzing this feedback, BAS can pick up and adjust occupants' choices with time, continuously improving comfort control and satisfaction [91].

6.2.2. IAQ

Traditional ventilation systems operate on static schedules, which usually fail to respond to real-time air quality fluctuations leading to stale air, increased CO_2 levels, and buildup of pollutants. IoT sensors calculate variables such as particle matter (PM), volatile organic compounds (VOCs), CO_2 levels, humidity, and temperature to assess indoor air quality. IoT-BAS analyzes this data in

Table 10
Articles related to emission monitoring and reporting, sustainable practices, and renewable energy integration.

Reference	Topic	Techniques	Advantages
Haidar et al. [95] (2018)	Reduction of CO_2 Emissions in smart buildings using IoT	• The use of dispersed IoT devices to control and inspect the generation, distribution, and consumption of electricity. • An optimization model integrated into smart meters.	• Establish a constructive interaction between consumers and both renewable and non-renewable electricity providers through smart meters. • Consumers declare their necessary electricity amounts, and suppliers disclose their energy accessibility. • Enhances energy efficiency and reduces associated costs and CO_2 emissions.
Anand et al. [96] (2020)	Control of CO_2 emission in residential buildings using IoT and cloud	• The Regulated Control Ventilation controller integrated with the IoT utilizes pure air regulation and is activated when CO_2 absorption exceeds a certain threshold.	• The prototype made using IoT helps in continuous monitoring through cloud technology • This method saves tons of carbon emissions and significantly reduces the energy consumption of air conditioning facilities.
Bunly and Oeurn [97] (2020)	Sustainable energy solutions of the future using IoT devices and renewable energy sources	• Combines solar power with a centralized grid and uses IoT smart devices to regulate electricity consumption online.	• Effective in addressing issues like poor energy efficiency, high expenses, and the limited functionality of current systems • Improves access to clean energy for the well-being of the society and the economy.
Zang et al. [98] (2021)	IoT-based smart carbon monitoring platform for small cities	• The real-time monitoring platform, leveraging IoT technology, facilitates advanced warning and decision-making through the use of identifiable, capturable, and shareable data.	• Implementation of a low-cost, high-precision, intelligent carbon-based system utilizing limited perceptual data.
Fernández et al. [99] (2022)	Control and Monitoring of CO2 Concentration in Existing Buildings using Low-cost IoT devices	• A low-cost IoT-based CO_2 measurement device is designed, developed, assembled, and prototyped with open programming for remote monitoring.	• Aggregating all data in the cloud helps for further analysis and integration with other smart systems within the building. • Helps to control and monitor CO_2 levels and, interact with HVAC systems.
Olatomiwa et al. [100] (2023)	IoT-based visualization platforms for tracking household carbon footprints	• The IoT platform employs sensors to illustrate the impact of household activities on carbon emissions.	• The systems allow organizations and individuals to monitor their carbon footprint, pinpoint opportunities for emission reduction, • Make informed decisions regarding energy consumption.
Singh et al. [101] (2023)	Review of current methods for sustainable development by carbon emission reduction	• Green building rating systems, sustainable materials, renewable energy, intelligent greenhouse gas procedures, life cycle evaluations, carbon capture and storage, and building management systems.	• Facilitate sustainable development by reducing and quantifying carbon emissions. • Gives lower energy costs, enhanced indoor air quality, and greater efficiency in resource use.
Gebreslassie et al. [102] (2023)	Design of sustainable buildings with renewables	• The design incorporates sustainable energy sources, including solar panels and wind turbines • Optimized through software like Autodesk Revit, and Dynamo and integrating with smart grids and IoT.	• Maximizes the efficiency of renewable energy from wind turbines and solar panels. • They are further optimized for enhanced performance through intelligent mechatronic system methods.

real time and provides insights into IAQ conditions, identifying potential sources of pollution or discomfort [92]. When the pollutant levels exceed safe thresholds the IoT-based BAS adjusts ventilation rates and airflow patterns based on IAQ measurements and occupancy levels to ensure adequate air exchange and freshness maintaining a healthy and comfortable indoor climate.

6.2.3. Visual and thermal comfort

Visual comfort decreases glare and improves the visual clarity of the occupants. Conventional systems depend on static temperature and lighting presets, which usually fail to adapt to user preferences, the external environment, and building usage patterns. Harnessing IoT sensors in building automation improves the occupants' visual comfort by considering the sunshine level, potential glare in the occupant's field of view, and view to outdoor satisfaction [93]. The thermal comfort conditions are assured by the measurement of indoor temperature, humidity, and radiant heat by the IoT sensors. BAS uses this data to adjust HVAC settings, such as heating, cooling, and airflow distribution, to maintain optimal thermal comfort levels for occupants [94]. Moreover, the cloud-based IoT platforms allow users to customize their local thermal and lighting choices through mobile apps or smart devices, ensuring comfort tailored to their needs.

6.3. CO_2 reduction

IoT-based BAS continuously monitors the CO_2 levels, energy consumption, and pollutant emissions through IoT sensors placed throughout a building. It can track and monitor building carbon emissions, providing valuable data for carbon offsetting initiatives. The cloud-based monitoring provides real-time observance of CO_2 levels. Quantifying CO_2 emissions and identifying emission hotspots enables building owners to implement carbon reduction strategies. It improves

- Emission Monitoring and Reporting
- Sustainable Practices and Renewable Energy Integration

The works related to techniques for CO_2 reduction, their advantages, and the integration of renewable energy are provided in a detailed manner in Table 10.

Table 10 emphasizes IoT and related technologies to reduce CO_2 emissions in smart and sustainable buildings. Techniques include deploying distributed IoT devices for electricity management, using smart-meter optimization models, integrating IoT with regulated control ventilation systems, and combining solar power with centralized grids. The advantages of these approaches include enhanced energy efficiency, reduced costs and CO_2 emissions, real-time monitoring, improved access to clean energy, and better decision-making regarding energy consumption. Additionally, IoT-based systems allow for monitoring and managing carbon footprints and optimizing renewable energy sources in building designs.

6.3.1. Emission Monitoring and Reporting

IoT sensors integrated into BAS continuously monitor energy consumption, fuel usage, and other activities contributing to emissions reduction within buildings. These sensors get up-to-date energy data, combustion processes, and environmental conditions, providing valuable insights into emission levels and trends [103]. It enables tracking, managing, and reducing greenhouse gas emissions in buildings. Aggregating and visualizing emission data through IoT dashboards enables stakeholders to identify emission hotspots, assess performance against sustainability goals, and make wise choices to lower emissions and improve environmental performance [104].

6.3.2. Sustainable Practices and Renewable Energy Integration

IoT-BAS enables the implementation of various sustainable practices and the incorporation of renewable sources of energy through the following strategies.

- ***Energy efficiency optimization***: BAS utilizes data analytics and IoT sensors to minimize building energy use. By monitoring energy consumption patterns, identifying inefficiencies, and implementing energy-saving measures, IoT-BAS helps reduce overall energy demand and promote sustainable practices.
- ***Demand response management***: IoT-BAS integrates with demand response programs to adjust building operations in response to grid conditions, peak demand periods, or energy price fluctuations. It reduces energy consumption during peak hours, helps alleviate strain on the grid, and supports incorporating alternate energy sources.
- ***Integration of renewable energy:*** The assimilation of renewable energy sources like wind turbines, solar panels, and geothermal systems within building energy systems is made easier by IoT-BAS, By optimizing the usage of onsite alternate energy generation and storage, it lessens dependence on fossil fuels, lowers carbon emissions, and promotes a transition to clean energy sources.
- ***Smart grid integration***: IoT-BAS integrates with smart grid technologies to minimize the use and distribution of energy based on dynamic grid conditions and renewable energy availability. Leveraging IoT sensors and communication protocols enables buildings to participate in grid-balancing activities, increase renewable energy utilization, and support grid stability and resilience.
- ***Energy storage management:*** IoT-BAS manages systems for storing extra renewable energy for later use, such as thermal storage and batteries, or to supply backup electricity in the event of a grid failure. It optimizes energy storage operations, enhances grid flexibility, improves energy reliability, and promotes sustainable energy practices.

Integrating sustainable practices and renewable energy sources within IoT-BAS has transformed building operations by supporting efficient resource usage, lower reliance on fossil fuels, and enhanced environmental performance. By harnessing continuous energy monitoring, intelligent optimization, and smart grid interactions, IoT-BAS dynamically adjusts energy consumption, prioritizes solar and wind energy usage, and minimizes energy waste through demand-side management. These advancements improve energy efficiency and contribute to reduced emissions in buildings that align with sustainability goals.

7. Research gap and recommendations for future work

After a detailed literature review, it is clear that while IoT-based BAS offers improved energy efficiency, better occupant comfort, and CO_2 reduction, there remain significant research gaps. The key challenges associated with integrating IoT-BAS, particularly interoperability, security, and scalability, have not been sufficiently explored, limiting their large-scale deployment in commercial buildings and smart cities. Fig. 10 highlights the key challenges and solutions for IoT-based BAS. Table 11 summarizes the challenges in the IoT-BAS and the effective solutions to solve them using recent technologies.

Table 11 tackles IoT challenges through various solutions. Semantic interoperability is addressed using web-based methods, middleware, agent-oriented techniques, and ontologies. Scalability improvements are achieved through edge computing, layered edge-based platforms, distributed sensing networks, and specific techniques for LoRaWAN. Security and privacy are enhanced using context-based permissions, dynamic analysis, lightweight authorization methods, cryptographic solutions, and trust frameworks. Interoperability is facilitated by gateways, virtual networks, open APIs, semantic web technologies, and middleware.

7.1. Interoperability

IoT devices come from various manufacturers, and ensuring seamless communication and compatibility between these devices can be challenging. Standardization efforts are ongoing, but achieving true interoperability remains a hurdle. Firstly, industry-wide adoption of standards such as BACnet, Modbus, MQTT, and OPC UA promotes a common framework for communication and data exchange. Open APIs provided by manufacturers enable third-party developers to integrate devices seamlessly into the BAS. Middleware solutions and protocol translators bridge communication between devices using different protocols or data formats [116].

7.2. Security and data privacy

With an increase in connected devices, the attack surface for cyber threats expands. IoT devices, if not properly secured, can become entry points for hackers to access critical building systems or even launch larger-scale attacks. BAS collects vast amounts of data about building occupants, usage patterns, and environmental conditions. Safeguarding this data and ensuring compliance with privacy regulations is crucial but complex, especially considering the potential for data breaches [117,118]. Implementing robust authentication and access control mechanisms helps prevent unauthorized access to IoT devices and BAS infrastructure. Utilizing encryption techniques such as Secure Sockets Layer(SSL)/Transport Layer Security(TLS) ensures secure communication between devices and data transmission over networks. Employing Intrusion Detection Systems (IDS) and security monitoring tools enables real-time detection of suspicious activities and potential threats. Regular software updates and patch management help mitigate vulnerabilities in IoT devices and software platforms [119].

Furthermore, incorporating privacy-enhancing technologies such as anonymization and data minimization techniques reduces the risk of exposing sensitive information about building occupants and operations. Conducting privacy impact assessments helps identify and address potential privacy risks associated with data collection, storage, and processing.

7.3. Scalability

As buildings grow or undergo renovations, the BAS must scale accordingly. Ensuring IoT infrastructure accommodates additional devices and functionalities without significant disruptions or performance degradation poses a challenge [120]. Initially, adopting modular and distributed architectures allows for the seamless addition of new devices and functionalities as the building expands or requirements change. Utilizing cloud-based IoT platforms enables the automatic scaling of resources to accommodate growing data volumes and device counts. Employing edge computing capabilities reduces the dependency on centralized processing, improving scalability by distributing computational tasks closer to IoT devices [121]. Standardizing interfaces and protocols facilitates interoperability between different components, simplifying the integration of new devices into the BAS ecosystem. Additionally, leveraging scalable communication technologies such as LoRaWAN or Narrow Band (NB)-IoT enables efficient connectivity for many devices over extended distances. Finally, conducting regular performance assessments and capacity planning ensures that the BAS infrastructure remains scalable and capable of meeting evolving demands [122].

Even though the proposed solutions address interoperability, security, and scalability challenges in IoT-BAS, their practical deployment in buildings needs structured implementation strategies. So, it is essential to explore the practical implementation of this research outcome in buildings.

7.4. Practical impacts on buildings

The practical implementation of the IoT-driven BAS in buildings is achieved through systematic planning in the integration

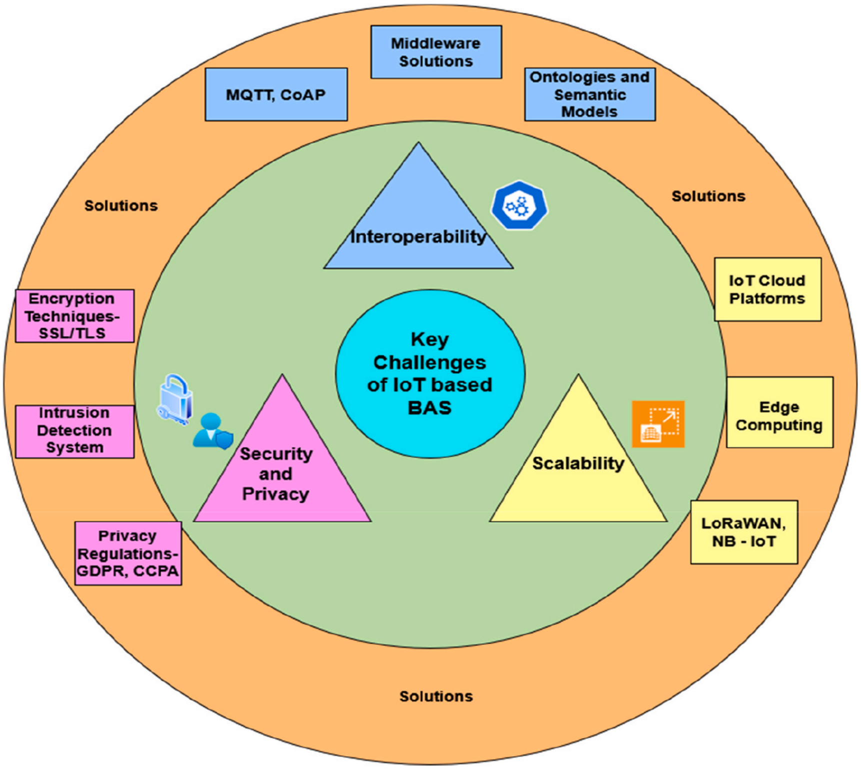

Fig. 10. Key challenges and solutions for IoT-based BAS.

Table 11
Articles related to interoperability, security, privacy, and scalability challenges in IoT-BAS and solutions to solve them.

Reference	Challenge	Solutions
Ganzha et al. [105] (2017)	Semantic interoperability	• Web-based Semantic methods along with middleware, agent, and service-oriented techniques
Ren et al. [106] (2017)	Scalability	• Edge computing creates scalable IoT platforms by utilizing transparent computing.
Zhou et al. [107] (2019)	Security and privacy	• Context-based permission, dynamic analysis simulation platform, dynamic configuration homomorphic encryption, and anonymous protocols
Noura et al. [108] (2019)	Interoperability	• Gateways, virtual networks, networking technologies, open API, semantic web technologies, and open standards
Javed et al. [109] (2020)	Scalability	• A layered, edge-based IoT platform improves heterogeneity, interoperability, discovery, and scalability
Chanal et al. [110] (2020)	Security and privacy	• Lightweight methods for authorization and authentication, Cryptographic security solutions
Rahman et al. [111] (2020)	Semantic interoperability	• Ontologies, middleware, and semantic web.
Ashwin Karale et al. [112] (2021)	Security and privacy	• IoT trust frameworks such as Hawk, Enigma, and Trusted Execution Environments (TEE) to tackle privacy issues. • Standards developed by international organizations such as ISO, IEC, ITU, and IEEE offer individuals and organizations a universal stance on IoT security • Smart contracts are considered for authorization by IoT laws such as UETA and ESIGN.
Martikkala et al. [113] (2021)	Interoperability of IoT platform	• The introduction of a classification system based on the functions performed by IoT systems, • Middleware to connect various IoT platforms
Anik et al. [114] (2022)	Scalability	• Building Data Lite, utilizing Raspberry Pi computers, a distributed sensing network, and a centralized server, offers a scalable and portable IoT solution.
Jouhari et al. [115] (2023)	Scalability	• Spreading Factor, logical, and frequency channel assignments, along with new network topologies, enable LoRaWAN to connect a larger number of end devices efficiently.

methods, interoperability solutions, cybersecurity frameworks, and scalable architectures. Deploying standardized communication protocols (MQTT/BACnet) guarantees smooth interaction between IoT devices and conventional BAS, facilitating effective data exchange for real-time automation. Applying cyber security measures, including anomaly detection algorithms, intrusion detection systems, and encryption techniques, improves data protection, ensuring the safe operation of smart buildings. Utilizing cloud-edge hybrid architectures that balance the local edge processing with cloud-based intelligence allows efficient scalability and real-time automation in IoT-BAS.

Moreover, cloud-based predictive analytics assist IoT-based BAS to optimize HVAC and lighting systems based on real-time occupancy and environmental conditions. Employing IoT-integrated adaptive facades and smart shading systems dynamically regulates thermal comfort and daylight usage, minimizing the energy demand. The successful deployment of these solutions in commercial buildings, apartment complexes, and industrial facilities greatly enhances energy savings, user comfort, and CO_2 reduction, supporting sustainable building practices and smart city initiatives.

7.5. Recommendations for future work

Future studies in IoT-based BAS need to focus on integrating AI methods like reinforcement learning for autonomous decision-making, improving cyber-physical systems security with integrated frameworks, investigating sustainability strategies, and optimizing edge intelligence for effective resource allocation and real-world adaptation. Furthermore, the emphasis could be on enhancing human-machine interaction through user-friendly interfaces, proactive lifecycle management through predictive maintenance methods, and integrating BAS with larger smart city projects for comprehensive urban management [123]. AI-driven BAS, seamless connectivity, blockchain security, digital twins, and scalable architectures will drive this field, towards more intelligent, resilient, and sustainable built environments.

8. Conclusion

This review analyzes the vital role of IoT-BAS in advancing towards sustainable building automation methods. The thorough investigation shows that through sophisticated monitoring and control mechanisms, IoT-enabled BAS dramatically increases energy efficiency, improves occupant comfort, and reduces CO_2 emission. Furthermore, advanced, context-aware technologies that adjust to user choices and ambient situations significantly enhance personalized comfort and indoor environmental quality. This study provides a holistic evaluation of IoT-BAS for energy efficiency, comfort, and sustainability. It also addressed the key challenges of interoperability, security, and scalability for IoT-BAS integration by finding practical solutions, including standardized communication protocols, strong cybersecurity frameworks, and hybrid cloud-edge architectures. These strategies improve system flexibility, security, and scalability, making IoT-BAS more durable and adaptable to modern smart building demands.

Specifically this review deeply explores IoT-driven BAS for energy optimization, occupant-centric automation, and sustainability goals within a single framework. By synthesizing recent advancements, identifying research gaps, and proposing integrated solutions, this research provides a clear roadmap for the future development of IoT-based BAS. As we advance, research and innovation become necessary to overcome challenges and fully utilize the immense potential of IoT-based BAS. So, future research should delve into AI-driven autonomous BAS, enhancing interoperability through open-source frameworks and building blockchain-based advanced cybersecurity mechanisms to ensure robust, scalable, and efficient IoT-based smart buildings. With concerted efforts and strategic integration approaches, IoT promises to transform building automation and open the door to more intelligent, sustainable, and resilient buildings.

CRediT authorship contribution statement

N. Sivasankari: Writing – original draft, Methodology, Conceptualization. **P. Rathika:** Writing – review & editing, Supervision.

Funding

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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