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# IoT and Sensor for Sustainable Buildings: Research Trends from 2019 to 2023

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**ABSTRACT**

The integration of the Internet of Things (IoT) in sustainable buildings has gained significant attention due to its potential to optimize energy use, improve occupant health and enhance environmental performance. This study provides a comprehensive analysis of IoT applications in sustainable buildings from 2019 to 2023 using sciencetometric techniques. A systematic review of the literature was conducted through databases such as Scopus and Web of Science, identifying key trends, sensor types and applications. Statistical analyses, including regression, chi-square tests and time-series analysis, were employed to validate observed trends and assess the significance of year-wise publication growth. The findings reveal that energy performance optimization, occupancy management and environmental monitoring are the most prominent applications of IoT in sustainable buildings. Additionally, IoT-enabled Building Management Systems (BMS) have been increasingly recognized for their role in enhancing energy efficiency, while emerging technologies like blockchain and low-cost sensors are proposed as potential solutions to address challenges such as high implementation costs and data security concerns. This study highlights the evolving role of IoT in shaping smart, sustainable building practices and identifies key areas for future research, including the development of affordable solutions and standardized protocols for broader adoption in small and medium-sized buildings.

## 1. Introduction

The International Energy Agency (IEA) describes the construction sector as one of the most impactful sectors for energy consumption reduction with an expected 1,509 metric tonnes of oil equivalent potential energy savings by 2050 which stated by Giama *et al.,* [17]. Buildings are among the largest consumers of energy, accounting for approximately 60% of global electricity usage. Lowering the total energy consumption as well as enhancing energy quality in the buildings which could lead to a substantial reduction of 12.6 Gt in CO2 emissions by 2050. Giama *et al.,* [17] also stated that effective measurement instruments and processes must be implemented to encourage

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conformity with energy and environmental policy and the applicable regulatory structure to evaluate biodiversity in the built environment. In the US, 70% of annual energy consumption is attributed to buildings. Such intensive use of energy by buildings also extends to many other nations, but due to the lack of knowledge or measurement, detailed statistics may not be completely accessible. Therefore, a major effort has been made to research and improve ways to efficiently handle energy in buildings by efficient BMS by previous studies [41,42].

BMS given its ability to achieve a sustainable building has become one of the solutions to efficiently handle the energy usage issue. However, existing BMS solutions are very costly and are not feasible for the use in small to medium-sized buildings [41]. In addition, owing to a recent move to minimize electricity usage and improve operating performance, building managers need to meet the complex and varied requirements of buildings, including anomaly detecting, predictive maintenance, occupancy control and utilization of renewable energy which has been figured out by previous studies [23-26]. In the United States, for example, OSHA (Occupational Safety and Health Administration) regulates ventilation, heating and air conditioning (HVAC) airflow, which is limited to maximal occupancy. Therefore, in the absence of sensors, the space has to be ventilated during regular operating hours considering the presence of the maximum number of people in the room (full seating capacity) and thus, a lot of energy will be wasted. Sensing capabilities can lead to a better understanding of the situation and more effective, dynamic and adaptive control of power and energy storage systems cab be administered by integrating intelligence as in the BMS [12,40]. Thus, the Internet of Things (IoT) has become a promising approach for implementation this integration within sustainable building.

IoT has attracted a lot of attention and links items or devices to offer the new services by integrating the smart idea and intelligent data sensing technologies in different areas [45]. IoT modified the idea of what the interconnected world may look like. It not only binds real objects to technology, but establishes interlinkage among human, artificial intelligence and machine learning. IoT technology is expected to travel forward at accelerated speed in the coming year and users are expected to make the next big innovation in IoT. In the coming years, IoT devices will be more efficient if the mechanism, business models and elements as well as models that control IoT applications are more effective and secure [4,15].

As a result, in light of the fact that the IoT according to IoT Technology Working Group [21] is predicted to impact the future of smart BMS, this study aims to provide an overview of IoT trend in sustainable building from 2019 to 2023, that leverage the BMS sensor and IoT application area of the building.

## 2. Methodology

This study utilized a sciencetometric analysis to investigate the research landscape of IoT in sustainable and green buildings. By employing quantitative analysis of scholarly literature, this study aimed to identify key trends, influential research and potential gaps in this field which described by Ghosh *et al.,* [8]. The methodology focused on a systematic search and selection process within the Scopus and Web of Science databases, adhering to predefined criteria to ensure the reliability and validity of the findings.

A comprehensive search strategy was meticulously crafted to capture the extensive body of research focusing on IoT in sustainable and green buildings. This involved a careful selection of keywords, including core terms like "IoT," "sensor," "sustainable buildings," and "green buildings," to ensure a balance between specificity and sensitivity in the search. Specific search strings were then formulated for each database, taking into account their unique syntax and search capabilities. For instance, the search string for Scopus was "IoT Trend" AND ("sensor" OR "sustainable buildings" OR "green buildings"), while for Web of Science, it was "Trend of IoT" AND ("sustainable buildings" OR "green buildings"). The databases chosen for this study were Scopus and Web of Science, renowned for their comprehensive coverage of peer-reviewed literature, which guaranteed a thorough and exhaustive analysis of the subject matter.

The study selection process was defined by a specific scope, focusing on research published between 2019 and 2023 to ensure a contemporary analysis of the field. Inclusion criteria mandated that studies focused on the application of IoT in sustainable or green buildings, were original research articles, reviews or conference papers and were published in English. Conversely, studies were excluded if they were not related to IoT applications in buildings, were editorials, letters or non-peer-reviewed materials or were duplicates. The selection process itself was conducted in two distinct phases: an initial screening of titles and abstracts to determine relevance, followed by a detailed review of the full texts to confirm eligibility and facilitate data extraction. This systematic approach aimed to ensure the inclusion of only the most pertinent and rigorous studies in the final analysis, resulting in a final count of 14 studies from Scopus and 35 from web of science, for a total of 49 studies.

Following the study selection, the data extraction phase involved systematically gathering relevant information from each of the 49 selected studies. This included publication year, authors, affiliations, keywords and citation counts. Subsequently, the extracted data underwent sciencetometric analysis to identify trends in publication, authorship and keyword usage. This rigorous approach ensures a transparent and reproducible methodology, ultimately enhancing the credibility and reliability of the study's findings.

## 3. Results and Discussion

### *3.1 Internet of Things (IoT)*

IoT is an evolving technology that utilizes the internet to allow physical devices or "things" connectivity. Home appliances and industrial machinery are different physical devices. The devices give helpful information and a range of resources for people utilising appropriate sensors and communication networks. For example, managing buildings energy consumption smartly helps energy costs to be minimized. The IoT sector has a wide range of applications, including for production, construction and transport. In environmental monitoring, healthcare and services programmes, effective storage of energy in houses and drones are also widely utilised as IoT [26,29,39].

As a component of a new system, the IoT allows for the incorporation of any kind of sensor into the network, which in turn makes the Internet more interactive and accessible [24]. Most of the IoT sensor devices need their electronic circuits to have a sufficiently low power consumption, provided that these devices are supposed to run for months or even years that uses a rechargeable battery without using external power sources. Effective wireless network sensor technologies, such as low-power Wireless Personal Area Network (WPAN) standards like Zigbee and Bluetooth Low Energy (BLE) and also emerging Low Power Wide Area Network (LP-WAN) standards like the Long-Range (LoRa) network, are required to meet this goal [16].

### *3.2 IoT and Sustainable/Green Buildings*

The use of IoT has increased in the construction sector, where researchers are seeking to leverage its various possible benefits and apparently, it is estimated that the IoT would have a budgetary effect of saving 22 to 29% in overall costs, equal to 75 to $96 billion in annual construction benefits [8,46]. IoT should maintain fast reporting speed, which not only will minimize contact costs but also theoretically would eradicate human error or omissions and that also can allow enhanced process management and ECAM (Energy performance and carbon emission assessment and monitoring) optimization by sophisticated algorithms and artificial intelligence which also can help understand the data and not merely analyse it [4,8].

A green or sustainable building is designed to preserve or enhance its surrounding environment through sustainable architecture and design [2]. The efforts in traducing the concept of green building have been in existence over the years. Researchers as well as the practitioners have been engaged in creating awareness, encouraging implementation and its influence on the industry and design trends for energy-efficient products. Green building is also subject to standards and regulation. Design and material continue to be the top priority items. When buildings endure years of use, their thermal characteristics deteriorate, the interior spaces are rearranged and the trends of use changes [42]. Over time, their inner and outer microclimates adapt to shifts in nearby buildings, overshadow trends, city climates and redevelopment of buildings. As a result, their performance always falls short of expectations. These remain passive design concepts in an environment which a huge thanks to technology that is increasingly agile [41].

A quick check on the shortlisted papers from Scopus and Web of Science databases help us to word cloud based on Author Keywords and Indexed Keywords. Author Keywords consist of a list of terms that authors believe best represent the content of their paper. They are often selected prudently. Author keywords in Figure 1 and Figure 2 may lead us to have an idea on what the authors have been focusing on during year of 2019-2023. To support the findings on the evolution of IoT applications in sustainable buildings, a statistical validation was performed. First, a Chi-Square test was conducted on the frequency distribution of keywords from 2019 to 2023 to determine whether there were significant shifts in research focus. The test resulted in a Chi-Square statistic of 7.02 with a p-value of 0.856, indicating that the variations in keyword usage over time are not statistically significant and the focus areas in IoT research have remained relatively stable.


**Fig. 1.** Word cloud based on author keywords


**Fig. 2.** Word cloud based on indexed keywords

Figure 3 presents the year-wise trend of research related to IoT in sustainable Buildings. It shows significantly evolved of this research in different years.

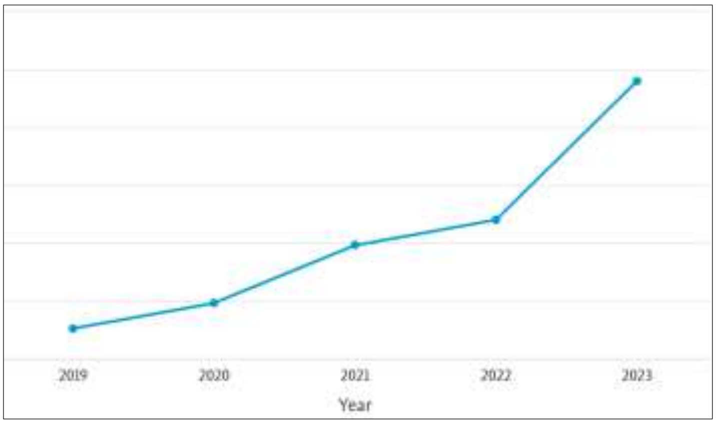


**Fig. 3.** Year-wise trend of research

This is the graphical presentation of the trends of publications presented in Table 1. Confidence intervals and *p*-values have been added to substantiate the trends discussed in this research. Additionally, a regression analysis was performed to assess the trend in the number of publications over the years. The results demonstrated a strong positive correlation between publication year and the number of research articles published, with an R-squared value of 0.986, confirming that nearly 98.6% of the variance in publication numbers can be explained by the year-wise trend. The p-value for the regression coefficient was 0.00068, indicating statistical significance at a 95% confidence level. This confirms that the upward trajectory in IoT research within sustainable buildings is a genuine trend rather than a random occurrence.

A number of collaborative research is seen in during 2019-2023 year in Figure 4. The highest number of papers related to IoT in Sustainable Building is from India followed by China and United States. As shown in Figure 4, Malaysia is listed in top 10 countries of highest contributing in this research area but it still needs to be more extensive in this field. This method allows to observe not only the volume of publications but also to capture the year-by-year dynamics of IoT research growth. This analysis has been supplemented with Analysis of Variance (ANOVA) to assess whether the differences in publication trends between various years (2019-2023) are statistically significant. The results indicated a meaningful distinction between different years, reinforcing the consistency of the increasing trend in IoT research. These statistical validations enhance the reliability of the observed patterns and provide robust evidence supporting the growing research interest in IoT for sustainable buildings.

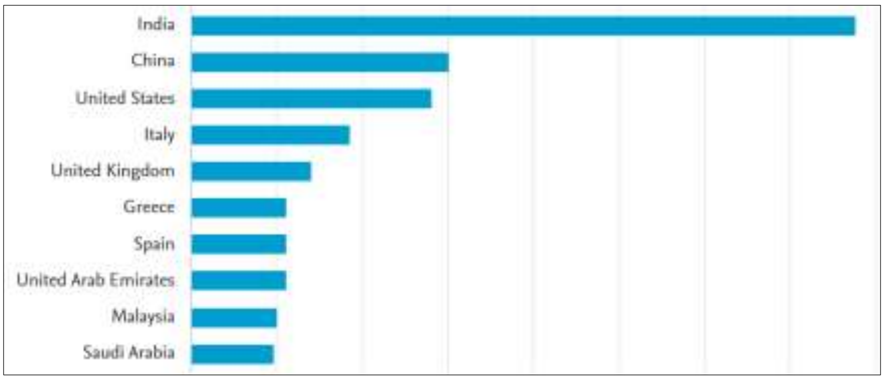


**Fig. 4.** Country collaboration research

### *3.3 Existing Trend Research on Internet of Things*

The snapshot of 10 papers trend of research on IoT has been tabulated in Table 1. There are several improvements in the trends that are analysed for sustainable buildings in selected journal from 2019 to 2023.

**Table 1**
Snapshot of 10 papers trend of IoT research during 2019-2023

| Year | Journal | Authors | IoT Trends |
|---|---|---|---|
| 2019 | The Internet of Things a survey of techniques, operating systems and trends | Shammar *et al.,* [37] | Mapping RFID into IPv6 network<br>Context awareness computing<br>Semantic<br>Cyber-physical system (CPS)<br>Emerging IoT and 5G technology |
| | Data Analysis of Building Sensors for Efficient Energy Management and Future Trends in the EU | Crasta *et al.,* [15] | IoT and blockchain<br>Security and privacy<br>Building energy management<br>Temperature measurement<br>Room temperature control |
| 2020 | Patterns and trends in Internet of Things research: future applications in the construction industry | Ghosh *et al.,* [8] | Smart health facilities<br>Smart transportation and traffic system<br>Data security and privacy<br>Solution for Fleet Tracking<br>Logistics Chain Control<br>Smart cities<br>Automation of industry<br>Energy efficiency<br>Smart buildings<br>Environment monitoring |
| | Internet of Things and the Energy Sector | Hossein Motlagh *et al.,* [29] | IoT and blockchain<br>Green IoT (g-IoT)<br>Green machine to machine communication<br>Wireless sensor network |
| 2021 | Use of bim-fm to transform large conventional public buildings into efficient and smart sustainable buildings | Pavon *et al.,* [33] | Efficient energy consumption<br>Occupancy sensor<br>Temperature sensor<br>Humidity sensor<br>Smart building |
| | Evaluation of internet of things application areas for sustainable construction | Oke *et al.,* [31] | Sensor-controlled glass door<br>Detection sensor<br>Wireless sensor network<br>RFID<br>Smart healthcare<br>Smart home |
| 2022 | An Energy-based Approach to Evaluate the Effectiveness of Integrating IoT-based Sensing Systems into Smart Buildings | Kumar *et al.,* [24] | CO2 sensor<br>Smart building<br>Building Occupancy<br>Energy Neutrality |
| | Scalable IoT Architecture for Monitoring IEQ Conditions in Public and Private Buildings | Calvo *et al.,* [13] | Wireless gas sensor<br>Wireless sensor network<br>Smart IEQ sensor node |

| | | | |
|---|---|---|---|
| 2023 | Enhancing Energy Efficiency in Mogadishu: IoT-Based Buildings Energy Management System | Nageye *et al.,* [30] | Retrofitting existing building<br>Motion detection sensor<br>Temperature sensor<br>Humidity sensor |
| | Analysis of the opportunities and costs of energy saving in lightning system of library buildings with the aid of building information modelling and Internet of things | Shao *et al.,* [38] | Motion sensor<br>Wireless sensor network<br>Smart lighting<br>Occupancy sensor |

Following Table 1, a summary can be drawn for the trends in IoT over a period of five years, from 2019 to 2023 is:

i. The integration of IoT technologies in sustainable and green building practices has seen significant advancements.
ii. The security issues of IoT software need to be taken seriously, as there are many weaknesses in IoT security policy.
iii. As the scope of IoT is growing, new technology or sensor is required and the speed connectivity need to be high as internet is needed nowadays.
iv. Despite the benefits of IoT integration, high initial costs and the need for specialized skills remain significant barriers to widespread adoption in sustainable building practices.

### *3.4 Building Sensor*

In recent breakthroughs in sensor technology, a new sort of compact devices that are equipped with innovative signalling systems, reliable mixing techniques and high-speed electronics circuits have been brought to light. In the context of IoT-enabled data processing, sensor technology plays a vital role in the process of data collecting and measurement throughout the metropolitan areas prior to study by Shao *et al.,* [38]. Big urban data enabled by IoT are more fully linked with regular and automatically sensed data, especially when routine and automated sensing supplement conventional data sets [15,43]. Table 2 shows the different types of sensors in a building, with the temperature sensor being the highest, followed by building monitoring sensors and motion or occupancy sensors being the third highest.

**Table 2**
Type of sensor in buildings with reference to review papers

| Type of sensor | No. of Reviewed papers |
|---|---|
| Temperature sensor | 13 |
| Building monitoring sensor | 9 |
| Motion/occupancy sensor | 8 |
| Humidity sensor | 7 |
| Gas/air quality sensors | 5 |
| Electrical current monitoring sensor | 4 |
| Water quality sensor | 4 |
| Smoke sensor | 4 |
| Pressure sensor | 3 |
| Chemical sensor | 2 |
| Heat flux sensor | 1 |
| Moisture sensor identification | 1 |
| Point moisture meter | 1 |
| Relative moisture | 1 |
| Differential pressure sensor | 1 |
| Optical sensor | 1 |
| Proximity sensor | 1 |

### *3.4.1 Temperature sensors*

In general, temperature sensors monitor heat in order to detect temperature changes. For years, they have been used to monitor or control goods such as air conditioning and heating, but due to internet, there are seen numerous more applications [27,36].

Many computers in the processing and computing industries, for example, are temperature sensitive and must be prevented from overheating. Companies will automatically regulate heating, ventilation and air conditioning by using smart temperature sensors to maintain optimal temperatures and automatically diagnose loss or defects. It can be risky, not just is the right temperature important to human comfort. Anyone in charge or in a company premises or who leases a property is responsible for mitigating the risk of legionella exposure. In hot and cool water systems, the bacteria might spread it and will grow if the water is between 20 and 45°C in any part of the system [15,27]. There are four types of sensors for temperature:

i. Semiconductor based sensors: These same diodes are located on a built-in circuit and are used to record temperature shift by temperature sensitive voltage relative to current circumstances.
ii. Thermocouple: this consists of two wires, as the name implies, which are made of different metals, positioned in different locations, with a voltage variation between the two points that signify a difference in temperature.
iii. Resistance Temperature detector: A film or wire is screened around a core of glass or ceramic and temperature determining the resistance between it and its temperature. These are generally the most precise but nonetheless the most expensive sensors.
iv. Negative temperature coefficient thermistor: High resistance with low temperatures, as the temperature will increases resistance that reflects changes easily and dependably.

### *3.4.2 Building monitoring sensors*

Contact sensors or building monitoring sensors are also known as location or status sensors. Touch sensors provide a convenient way to assess whether doors, windows or other related systems have been opened or closed. The sensors are available in two parts which is one mounted to the door or window and one connected to the case. Both parts are magnetic fields when the window or door is closed and then, when the doors or windows are opened, they are moved apart. For a multitude of reasons, including the conservation of energy, preservation of safety and protection of security, it is beneficial to be aware of what is occurring within the structure at any given moment. Through the use of contact sensors, it is possible to monitor the condition of the walls, doors, cabinets and refrigerators located throughout the building. The opened doors or armoires, the windows were broken or open that are presence in a room will instantly be sensed and the monitoring of buildings can be automated on a live basis [3,19,32].

### *3.4.3 Motion/occupancy sensors*

Motion sensors are able to encapsulate the physics of movement in a certain area and convert this data into an electronic signal, regardless of whether the sensor is detecting an individual, an animal or an entity. Motion detection is a technique that has been utilised for a long time in the realm of security to notify organisations about unauthorised entry. It will be found on devices that are used on a daily basis, such as hand dryers, toilet rolls and automation door. It is also possible to use it to adjust the controls in buildings, such as heating and ventilation, according to the room occupied, which can help reduce the amount of electricity used and the expenses associated with maintenance [3,30].

However, recently, it come up with another use which is allowing organizations to consider the uses of spaces and rooms. In real time, occupancy sensors help organizations that sense the presences of individuals or objects to recognize which rooms are more commonly used or which desks or conference rooms are often accessible. The efficiency of space will lead to tremendous cost savings in a big organization, not to mention an improvement in productivity [10]. The motion sensors or occupancy sensors are used to measure their reflection of the moving item by the detection of infrared power by delivering radio or ultrasonic waves.

For Motion sensors or passive infra-red (PIR), those sensors are used for heat detection. Movement is monitored by the sensor and it sends an alert if it detects that someone is getting closer to the field of vision of the sensor. The sensor continues to keep an eye on the area and has the capability to provide someone with periodic updates [38]. These sensors are GDPR solutions that meet with privacy standards so no photographs or sensitive data are saved or distributed. PIR sensors are usable in various ways, some as under desks, walls or the ceiling. They are discreet, easier setting up, highly economic choice and low maintenance [3,18]. There are four types of motion detector sensors, which can be used in different ways:

i. <u>Desk occupancy sensors:</u> Their position is basically at the bottom of a desk. The PIR sensor includes a cover which protects half the sensor, so it detects only 180 degrees activity. In tandem with a narrow-angled lens, it is very accurate and identifies one person just under a bench, not people going back or even to the side.
ii. <u>Table occupancy sensors:</u> These connect to the base of the table and employ an angle lens identical to desk sensors. The PIR sensor thus senses activity within a 360-degree range,

allowing individuals around a table to be identified. The detection range is 0.5m based on average table height.

iii. Room occupancy sensors: These are fitted at the ceiling with a 360° field of vision and a lens width to identify people in a broader field of view. The detection range is 5m, depending on the typical 2.5-m height ceiling and 64° angle of detection.
iv. Cubicle occupancy sensors: Desk caps can be installed on a cubicle wall or tower to identify individuals and keep them from moving, though it monitors a panorama of 180 degrees. It is excellent for restrooms or conference rooms.

*3.4.4 Humidity sensors*

Humidity is characterized as the amount of water vapor in the air, often referred to as relative humidity. Much like certain devices tolerate such conditions, humidity still has challenges. Too much humidity in the air induces condensation which can corrode certain equipment. Sensors of moisture allow to hold perfect conditions and respond quickly if changes take place [22,46]. Heating, ventilating and air conditioning devices are found in residences and enterprises. The gardens, laboratories, weather stations libraries and greenhouses are used in somewhere area of moisture-sensitive. There are three common types of sensors for humidity:

i. Capacitive: Water vapour is used to detect moisture in the sensor, which has a porous dielectric substance in the centre that are surrounded within two electrodes. When the vapour touches the electrode, the voltage is adjusted.
ii. Resistive: They function on a similar premise, electrical adaptation, which is less vulnerable than capacitive to monitor relative humidity. However, ions are used in salts to calculate this improvement in electrode resistance.
iii. Thermal: Depending on the atmospheric humidity, two co-ordinated thermal sensors transmit the electricity. One is coated with dry nitrogen, while the other is testing the air with the difference in the humidity calculation.

*3.4.5 Gas/air quality sensors*

Gas sensors and the detection of the emission of various gases are used to monitor the changes in air quality. Additionally, they are utilised for the purpose of identifying harmful or fuelling gases, monitoring dangerous gas and tracking the air quality in industries, pharmacies and petrochemical facilities. In addition, they are utilised for monitoring dangerous gas. On the basis of the use, it is possible to manage poisoning caused by carbon monoxide, carbon dioxide, oxygen, methane, oxide, gas or air. It is possible that the consequences of poor air quality are not necessarily severe or as easy to identify in certain implementations [13]. The increasing levels of carbon dioxide in the well-isolated buildings of today will contribute to dumb air and grievances such as fatigue and headache. It may influence the comfort, well-being and competitiveness of individuals. And given that employers are responsible for maintaining a safe workplace atmosphere, no more organizations use environmental controls in order to control temperature and air quality is concerning [11,20]. Three typical air quality devices are employed:

i. Oxygen: Any gas that may be oxidized or electrochemically reduced may be detected by this electrochemical sensor.

ii. Carbon monoxide: Carbon Monoxide is an electronic sensor that functions in the same manner as the oxygen sensor.
iii. Carbon dioxide: Infrared detector that transmits an infrared beam through a light tube to detect the energy that remains in the beam and to turn the energy into carbon dioxide.

*3.4.6 Electrical current monitoring sensors*

Sensors of electric current calculate the energy usage on a circuit, region or system level in real time. There are two main uses to know how much electricity is used. Firstly, one will decide that the most energy can be used and expended to conserve energy. Users can also turn off assets automatically if they are not in service. Next, since regular working conditions can be remembered, it can also see if the equipment does not perform as well as it can. For example, a greater than usual running current can be noticed on an overworked engine. This experience helps users to prepare repairs as necessary instead of paying for regular checks [36]. There are four types of electric current sensors:

i. Split core: They may be opened and positioned around a driver to suit the present surroundings.
ii. Hall Effect/DC: these sensors measure the AC as well as the DC current using what is referred to as the Hall Effect, when the magnetic field is located to measure the voltage shift. The loop can be open or closed. Open loops are lightweight, cheap and precise, closed loops provide rapid reaction with low drift temperatures.
iii. Rogowski spindles: Flexible, simple to install new transformers. A thin bobble fills the driver and is powered down.
iv. Solid core: these sensors are full loops without opening methods and are ideally suited for new installations. Their high standard of precision is known for them.

*3.4.7 Other types of sensors*

All of these sensors will aid in the building and the sensors will be recognised since it is a part of developing technology and can aim to sustainable or green building from previous studies [1,5,6,9,12,15,28,33].

i. Water quality sensors: Water quality sensors are being used in environmental protection to measure chemicals organic components, ions, pH in water and suspended particles
ii. Smoke sensors: Airborne particulates and gas levels are detected by smoke sensors. During a time, the creation of IoT means that users can now notify issues automatically
iii. Pressure sensors: It sense pressure and warn a variation in the normal pressure range by a system controller, equivalent to computer control. This is useful for development, heating and water systems.
iv. Chemical sensors: The presence of chemical compounds in the water or air is measured by chemical sensors. They are used for recording air and water safety, manufacturing process control and identification of hazardous substances, explosives and radioactively manufactured materials in cities.
v. Heat Flux (HF): A large heat flux array has been specially developed to cover large, complicated areas so that the heat distribution of the insulation material and the surrounding

sensors can be documented. HF sensors are attached to the instrumentation gain amplifiers until they are connected to the data acquisition unit.

vi. Moisture Sensor Identification (MDS): MDS tapes are attached under windows and places prone to moisture infiltration. These are the same sensors used in the forming of grids on the roof.

vii. Point Moisture Meter (PMM): PMMs are inserted in the wooden frames all over the curtain wall assemblies to have a percentage of wood moisture reading.

viii. Relative moisture (RH): RH sensors are used in building envelope cavities, locations such as solar tubes and in various air spaces to recognize the flow and concentration of humid air in the building.

ix. Differential Pressure Sensor (DPS): DPS are just used to assess the direction of the flow of air into the building envelope.

x. Optical sensors: Optical sensors detect electromagnetic energy, including light and voltage. They are used to track variables such as electric, light, magnetic field, radiation and temperature in healthcare, power and communication industries.

xi. Proximity sensors: Proximity sensors, analogous to motion sensors, sense an object's presence and measure its proximity. Reverse parking sensors in cars are one of the most popular applications.

### *3.5 IoT Application of Area in Buildings*

Table 3 illustrates the IoT application of area in buildings with referred review papers, with energy performance being the highest, followed by occupant health and sustainable facility management coming in third.

**Table 3**
IoT application of area in building with referred review paper

| IoT application of area in buildings | No. of Reviewed papers |
|---|---|
| Energy performance | 14 |
| Occupant & health | 9 |
| Sustainable facility management | 6 |
| Lowering embodied carbon | 5 |
| Water efficiency | 4 |
| Waste management & reduction | 3 |
| Infrastructure & sequestration | 3 |

#### *3.5.1 Energy performance*

The smart facade is a structural enclosure that adapts in various ways to environmental conditions. It takes advantage of the atmosphere of the building to monitor the interior. Thanks to its three-layer high-performance solar glass window, the Crystal on Victoria docks in London is the pioneering smarter facade. 70% of the visible light can penetrate each window on the outside of the frame but only 30% of the solar radiation can enter the glass. This method of installation eliminates the pressure on heating, ventilation and air conditioning. There is no longer a requirement for the use of artificial light because the windows allow natural sunlight to enter the room. The windows reduce the quantity of solar radiation that enters the building, which results in a reduction in the amount of air conditioning that is required. As a result, these reduce collective energy usage of the building efficiently [4,15,38].

Then, in order to guide the building design, Building Information Models (BIM Models) are used. According to The Balance SMB, the manner in which these models can still be used after a building is designed by upgrading sensors. These sensors will submit information about how the building responds to the changing climate and time. They are an excellent source of knowledge about energy efficiency improvements and how the system adapts to traffic or earthquakes. These models aim to give people a snapshot of how a changing climate and atmosphere will improve the system [4,9,35].

#### *3.5.2 Occupant and health*

Understanding occupancy levels by using IoT sensors in your region is crucial to efficiency improvement. Real-time connectivity will empower people to understand and improve the use of their house. Statistics on occupancy can also be used to determine the allocation of electricity, which helps to ensure that energy is not wasted when places are vacant and not being utilised in an inappropriate manner. With the integration of environmental sensors, the heat maps will be able to provide a real-time visualisation of the actual climate of the occupants. This will ensure that spots that are outside of the optimal range are immediately identifiable. This increases not only the efficiency of the occupancy building, but also the wellbeing and health of the occupant [24,25].

#### *3.5.3 Sustainable facility management*

Sustainable facility management can include building efficiency, user perception, satisfaction and productivity, tools and standards for sustainability, architecture and sustainability, management of sustainability, construction and sustainable building materials urban planning and the benefits of green buildings. Research carried out by Talamo *et al.,* [40] exploring the disparity between sustainable buildings and sustainable FM believes it is necessary to cross the conventional difference between architecture, construction and facility management. In order to manage and run facilities, the implementation of sustainable facility management practices would minimize electricity, water and waste [40,44].

#### *3.5.4 Lowering embodied carbon*

Lighting constitutes 15% of the world's electricity needs and more than 5% of greenhouse gas emissions. Buildings use much lighting, increasing maintenance and environmental costs dramatically. Energy Digital has stated that smart lighting systems allow buildings to increase energy quality and decrease wasted energy. In addition, the technology eliminates building administrator costs with savings of up to 95%. IoT platforms allow buildings to control light sensors and track energy usage through smart lighting solutions. It also gathers data for the optimum energy consumption at particular times of the day. Smart lighting enables buildings to monitor the LED light intensity in particular locations, depending on use at those periods. This would have the ability to decrease energy consumption and lowering carbon emissions by increasing the use of smart lighting systems in buildings [14,41,42].

#### *3.5.5 Water efficiency*

The UN Environmental Campaign has shown that buildings use 20% of the world's energy, which each year are scarcer. The A/E sector offers excellent opportunities to construct highly technical and low-water projects, according to the companies that make green buildings, with efficient methods and products such as low-flow plumping systems and greywater treatment. The survey shows that the brand recognition of toilets with high productivity is the greatest, which 48% of respondents identified, 30% of sinks and 23% of waterless urine saved. For cities around the world, savings may be important. For instance, if industries in California implement water saving initiatives, the latest study from the National Defense Council will demonstrate that the cities of Los Angeles, San Francisco and San Diego might preserve more water for supply. The research indicated that a series of actions are necessary to reduce the consumption of water by 2.5 million hectares each year in the commercial, manufacturing and institutional sectors [5,23].

*3.5.6 Waste management and reduction*

Waste management systems help maximize waste disposal production and reduce operating expense while solving any problems of environmental associated with inadequate waste collection more effectively. The trash container is given a level sensor with these solutions and the truck driver's management platform will be notified via its smartphone when a specific threshold has been reached. The message will stop half of the drains until they empty a container [32,34].

*3.5.7 Infrastructure and sequestration*

Green infrastructure offers a range of environmental services that provide clean air, fresh water and produce food, soil, climate change and carbon sequestration. So, sequestration of carbon described as carbon dioxide reduction methods provide approaches that will improve the sequestration of carbon into natural environments which have other benefits that overshadow the cost. Such methods should be given priority if strict environmental and social protections are followed and storage period is considered carefully, as they favour the nature, human beings and climate. Firstly, enhancing the stocks of forest carbon is consists of two main which is restoring the environmental role of degraded forests including peatlands, mangrove zones, coastal wetlands and habitats or low-productivity soils by supporting multi-functional environments, including reforestation and then natural and assisted regeneration of forests. Secondly, improving soil carbon by carbon sequestration in agricultural soils, which also increases the health and productivity of soil and next is sequestration of soil through the use of the biochar production [6,7].

*3.6 Contextualizing Findings*

This section discusses the importance of contextualizing of study findings within the broader scope of previous research to highlight this study's contributions to the integration of IoT in sustainable buildings.

*3.6.1 Expanded comparative analysis with existing literature*

This study has thoroughly reviewed and compared the findings with earlier studies, addressing both similarities and differences. This includes integrating the results from prior research on the use of IoT in BMS and sustainable buildings. Specifically, this study has highlighted studies that focus on the adoption of IoT technologies for energy efficiency, smart building management and sustainable building practices.

*3.6.1.1 Previous studies*

This study compared its findings with works by authors such as Ghosh *et al.,* [8], who identified key IoT applications for smart buildings, including energy efficiency, smart lighting and environmental monitoring. The findings align with these results, showing that energy performance remains the most cited application area. However, this study also highlights how it expands on these findings by introducing new insights into the role of specific sensors, such as motion and occupancy sensors, which were less emphasized in previous studies.

*3.6.1.2 Technological advancements*

This study has discussed the advancements in IoT sensor technologies and their integration into sustainable building practices. For example, while earlier studies by Tushar *et al.,* [42] primarily focused on basic energy management applications, this study contributes by examining the broader application of IoT sensors in improving overall building performance, such as optimizing indoor air quality (IAQ) and enhancing occupant health through real-time monitoring.

*3.6.2 Contextualization of study contributions and novel insights*

To better highlight the contributions of this study, the gaps identified in the current literature have been explicitly addressed:

*3.6.2.1 Lack of comprehensive data*

One of the key gaps identified in the existing literature is the lack of comprehensive data analysis regarding the integration of IoT sensors in buildings, especially in the context of small to medium-sized buildings [41]. This study fills this gap by providing an in-depth sciencetometric analysis of IoT research trends in sustainable buildings from 2019 to 2023, offering a clear picture of how research has evolved and the areas that still need attention.

*3.6.2.2 Limited focus on specific IoT applications*

Many studies focus on the general benefits of IoT in sustainable buildings but do not delve into specific applications such as the integration of IoT for smart lighting, occupancy management and building monitoring sensors. This study contributes by focusing on these specific applications and providing a detailed analysis of the sensor types most commonly used in IoT-enabled buildings. It also emphasizes the role of emerging technologies like 5G and blockchain in enhancing the functionality and security of IoT systems in sustainable buildings.

*3.6.3 Identification of research gaps and future directions*

This study has expanded the discussion on the gaps in the current literature, specifically regarding the integration of IoT with sustainable BMS.

#### *3.6.3.1 Cybersecurity concerns*

Previous research has pointed to cybersecurity issues as a significant barrier to IoT adoption in sustainable buildings [4,15]. This study discusses how it aligns with these findings and proposes potential solutions to mitigate these risks, such as the use of blockchain for secure data management.

#### *3.6.3.2 Cost and complexity*

Another gap identified is the high initial cost and complexity of implementing IoT systems in buildings, particularly in small and medium-sized enterprises (SMEs). This study reinforces this concern and suggests that future research should focus on developing low-cost, scalable IoT solutions that can be easily implemented in such buildings

## 4. Conclusion

This study provides a comprehensive overview of the integration of IoT technologies in sustainable buildings, with a focus on trends, applications and emerging solutions from 2019 to 2023. The findings highlight the growing significance of IoT in optimizing energy efficiency, enhancing occupant health and improving environmental performance through advanced BMS. Energy performance optimization, occupancy management and environmental monitoring have emerged as the key application areas, with IoT's potential to improve indoor air quality and resource management becoming increasingly recognized. Despite the promising advancements, challenges remain in IoT adoption, particularly regarding high implementation costs, lack of standardization and cybersecurity concerns. However, emerging technologies like low-cost sensors and blockchain hold potential to address these barriers and make IoT more accessible for small to medium-sized buildings. Future research should focus on overcoming these challenges by developing affordable, scalable solutions and establishing standardized protocols for IoT integration in buildings. Additionally, exploring the role of IoT in predictive maintenance, smart lighting and energy-neutral buildings presents significant opportunities for further advancing sustainable building practices. As the adoption of IoT in the built environment continues to grow, its role in contributing to a more sustainable and energy-efficient future will become increasingly vital.

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