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INTERNET OF THINGS (IOT) ENABLED CARBON EMISSION MONITORING IN RESIDENTIAL BUILDINGS: A BIBLIOMETRIC ANALYSIS

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ABSTRACT

Carbon emissions from residential buildings have drastically increased in the recent past because of lifestyle changes. Hence, there is a critical necessity to implement carbon reduction pathways, and among them, carbon emissions monitoring can be identified as one of the prerequisites for carbon reduction. Many researchers have attempted to deploy various technologies for this purpose, such as the Internet of Things (IoT), Cyber-Physical Systems (CPS), and electricity big data to name a few. This research aims to review the adaptability of IoT for carbon emissions monitoring in residential buildings through a bibliometric analysis of key literature. Accordingly, a Scopus-based systematic review was conducted to analyse the journal articles related to the IoT, carbon emissions monitoring and residential buildings and their intersection. The bibliometrics techniques were used for the analysis of the results of the systematic review. As the primary implication of this research, the bibliometric analysis outcomes significantly contribute to identifying the number of published journals, leading journal authors, and countries active in this field. Accordingly, the outcomes reveal that the number of published articles has consistently increased over the last ten years. Further, the 'Journal of Energies' had published the highest number of articles. Secondly, the proposed framework gives important insights into the intersection of IoT, carbon emissions monitoring and residential buildings including the different types of carbon emission from residential buildings and potential outcomes from IoT-based carbon emission monitoring platforms.

Keywords: *Carbon Emissions Monitoring; Internet of Things (IoT); Residential Buildings***.**

1. INTRODUCTION

The 2023 Global Status Report for Buildings and Construction, which is published by the Global Alliance for Building and Construction hosted by the United Nations Environmental Program claimed that, CO_2 emissions from building construction and

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operation have surged to unprecedented levels in 2022 (United Nations Environment Programme, 2024). Further, it mentioned that both direct and indirect emissions from the residential sector hold a 17% share of total global carbon emissions, according to 2022 statistics and it has emerged a critical necessity to implement carbon reduction strategies focused on every sub-sector in the building industry including residential buildings (United Nations Environment Programme, 2024).

When focusing on carbon reduction pathways, carbon emissions monitoring can be identified as one of the key elements because it is beneficial for developing emission reduction plans and policies and post-analysis (Liu, et al., 2020a) IoT, CPS and electricity big data are some technologies can be utilised for carbon emissions monitoring. (Chawla et al., 2023; Devan et al., 2019; Liu, et al., 2020b; Mao et al., 2018; Zhou et al., 2023). Among these technologies, IoT can be recognised as a prominent methodology for carbon emissions monitoring due to its outstanding benefits such as real-time monitoring and the capability of in-depth analysis to determine trends and patterns in carbon emissions (Olatomiwa et al., 2023; Xu et al., 2022). Accordingly, this research paper aimed to review the adoptability of IoT for carbon emissions monitoring of residential buildings through systematic review of key literature as a way forward for future research.

In order to achieve the research aim, two (02) research objectives were formulated:

- To review the evolution of publications, prominent journals, and authors who had made most publications on the intersections of carbon emissions monitoring, IoT, and residential buildings, and
- To propose insights on different intersections between carbon emissions monitoring in residential buildings and IoT as a basis for future research.

2. LITERATURE REVIEW

2.1 CARBON EMISSIONS MONITORING IN RESIDENTIAL BUILDINGS

Carbon emissions from any typical building including residential buildings can be broken down into two main categories as; embodied emissions and operational emissions (Ibn-Mohammed et al., 2013; Izaola et al., 2023). Embodied emissions can be defined as *"the allocation of Green House Gas emissions that arise in the production of construction products of all kinds, their transport to and from the building site, the processes of building construction, maintenance, replacement, and deconstruction, as well as the end of life of building components and the building"* (Lützkendorf & Balouktsi, 2022). Further, Ibn-Mohammed et al., (2013) claim that embodied emissions can be categorised further as initial embodied emissions and recurring embodied emissions. Initial embodied emissions refer to the emissions that occurred due to the initial construction of the building (Ramesh et al., 2010) while recurring embodied emissions refer to the emissions from building repair and replacements (Ibn-Mohammed et al., 2013; Li et al., 2014). Building superstructures and substructures can be identified as the flashpoints of embodied carbon even though they can be varied based on the material usage and building design (Cang et al., 2020; Victoria & Perera, 2017). According to Akbarnezhad and Xiao, (2017), operational carbon emissions can be defined as "the operating carbon comprises of carbon emissions incurred during the service life of a building and includes the carbon emissions incurred in maintaining the indoor environment through processes such as heating, cooling, lighting, and the operation of appliances". Most of the researchers claim that operational emissions are higher than embodied emissions due to the continuous consumption of energy despite the building locations, occupancy patterns and utilising energy sources (Cao et al., 2016; Fenner et al., 2020; Huo et al., 2019). Operational carbon emissions encompass both direct emissions resulting from direct fuel combustion and indirect emissions from producing and distributing required products and services respectively (Hirano et al., 2020; Jiang et al., 2020; Zarco-Periñán et al., 2022; Zhang et al., 2015). According to statistical data, residential buildings are one of the main contributors to total carbon emissions from buildings. For example, residential buildings contribute to 12% of carbon emissions, which is equivalent to over 45 million tonnes of greenhouse gas emissions annually in Australia (Dcceew, 2023). In addition to that, on average, residential buildings emit 2,928 kg of greenhouse gas emissions per m^2 of gross building area throughout their lifecycle, according to Fan and Fang, (2023). Furthermore, according to Li et al., (2022) and Nejat et al., (2015), it is predicted that the energy usage in houses will increase in the future allowing further operational carbon emissions increments. Accordingly, these excessive carbon emissions create a critical necessity to implement carbon reduction projects and policies immediately. In this case, carbon emissions monitoring is the initial layout for implementing carbon emissions reduction plans and policies (Zhou et al., 2023). As reviewed in the literature, many researchers focused on applying different techniques such as IoT, Cyber-physical systems and electricity big data for real-time carbon emissions monitoring with the advancements in information technology (Chawla et al., 2023; Devan et al., 2019; Liu, et al., 2020b; Mao et al., 2018; Zhou et al., 2023). Among these technologies, IoT technology appears to be a promising solution for monitoring carbon emissions because it offers outstanding benefits for real-time carbon emission monitoring (Olatomiwa et al., 2023; Xu et al., 2022).

2.2 IOT-ENABLED CARBON EMISSIONS MONITORING

IoT can be identified as one of the novel paradigms for carbon emissions monitoring in different industries (Xu et al., 2022). IoT can be defined as *"a group of interconnected static and/or mobile objects such as devices equipped with communication, sensors, and actuator modules connected through the internet"* (Sengupta et al., 2020). The main advantage of using IoT for carbon monitoring is their ability for real-time data collection and analysis capabilities. This enables facilities to react promptly to reduce carbon emissions such as energy conservation measures and implement modifications as required (Olatomiwa et al., 2023). Furthermore, the capacity to offer in-depth analysis is another outstanding benefit of IoT-based carbon emissions monitoring (Xu et al., 2022).

However, various research attempts focus on adopting IoT for carbon emissions monitoring in different sectors including the building sector. For example, Mao et al., (2018) developed a real-time carbon emissions monitoring tool for prefabricated construction based on IoT; Tao et al., (2018) introduced an IoT-based carbon emission monitoring system for manufacturing prefabricated components; Zhang et al., (2021) formulated a smart carbon emissions monitoring platform for small cities based on IoT; Devan et al., (2019) established a vehicle emissions monitoring and alert system based on IoT; Martillano et al., (2017) launched an Android-based industrial emissions monitoring system using IoT; and Xu et al., (2023) developed a method for tracking and visualising embodied carbon of prefabricated buildings using IoT and Building Information Modelling to name a few. Despite the widespread use of IoT for carbon emissions monitoring in various industries, there is a scarcity of adopting IoT for monitoring carbon emissions in residential buildings.

3. RESEARCH METHODOLOGY

To complete the present study, a systematic review of literature was used as the methodological basis. Key literature published at the intersection of the fields of Internet of Things (IoT), carbon emission monitoring, and residential building was identified through a systematic review in the Scopus database. This Scopus-based review paper provides initial insights into the adoption of IoT for carbon emission and carbon emission monitoring in residential buildings from 2015 to 2024. Since there were no articles related to the intersection between carbon emission monitoring in residential building and IoT before 2015, the article search was limited to time period from 2015 - 2024. As the initial step of the review, a literature search was conducted in the Scopus database using the keywords 'Internet of Things', 'carbon emission', 'carbon emission monitoring', and 'residential building' to search titles, abstracts, and document keywords published from 2015 to 2024 [TITLE-ABSKEY ("Internet of Things" AND "Carbon Emission" OR "Carbon Emission Monitoring" AND "Residential Building")].

Initially, there were 132 articles that were further refined using the filters available on Scopus's search tool: (i) DOCUMENT TYPES=(Articles) AND (ii) SOURCE TYPE=(Journals) to identify high-quality literature. Accordingly, 95 journal articles were selected as the basis for bibliometric analysis. Bibliometric analysis was used to identify papers relevant to the review. As stated by Donthu et al., (2021) the bibliometric analysis technique has been highly used to evaluate the contributions of research scholars in various fields, patterns of publications, and the relationship between research findings. Hence, the analysis of literature was conducted by adopting two selected bibliometric indicators: the co-occurrence of words and the number of articles showing the intersection of the fields of IoT, carbon emission monitoring, and residential building. According to the Mokhtarpour and Khasseh, (2021), the number of articles reflects scientific output, providing a count of the quantity of works produced by a researcher, while co-occurrence facilitates the recognition of the specific network of a given type of research based on its development over the years.

Hence, the evolution of the number of journal articles published over the years, leading journals, leading authors, and leading countries on the intersection of IoT, carbon emission monitoring, and residential building were identified through the analysis of the evolving trends in the publication of journal articles over time. The literature was chosen based on selected bibliometric indicators to understand the intersection between IoT and carbon emission monitoring concepts in residential buildings.

4. RESULTS AND DISCUSSION

This section presents the key research findings related to two major areas; (i) Outcomes of bibliometric analysis, and (ii) Adopting IOT for carbon emission monitoring in residential buildings.

4.1 OUTCOME OF THE BIBLIOMETRIC ANALYSIS

As the initial step, the data derived through the Scopus-based systematic review were analysed using bibliometric analysis to track the adoption of IoT for carbon emission monitoring in residential buildings. The results, which were analysed for the period from 2015 to 2024, are organised under four key headings: (i) Evolution of the number of journal articles published on adopting IoT for carbon emission monitoring, (ii) Leading journals published on adopting IoT for carbon emission monitoring, (iii) Analysis of the leading authors in the field, and (iv) Analysis of leading countries on adopting IoT for carbon emission monitoring.

4.1.1 Evolution of the Number of Journal Articles Published on Adopting IoT for Carbon Emission Monitoring

In the systematic review, 95 journal articles published between 2015 and the first two months of 2024 were selected for analysis. The evolution of the number of journal articles published on Adopting IoT for carbon emission monitoring in residential buildings in the Scopus database is presented in Figure 1.

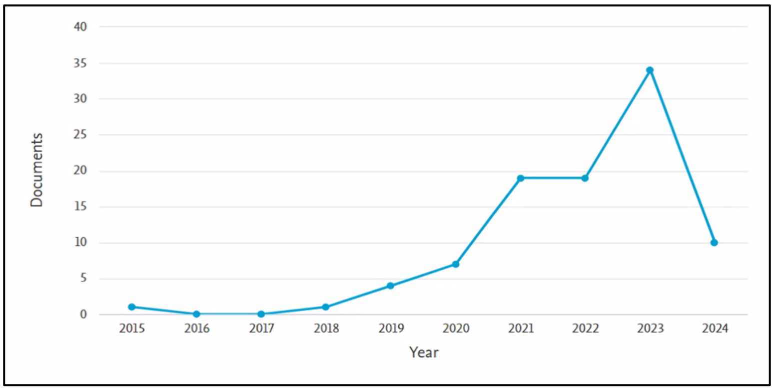

Figure 1: Evolution of number of journal articles

Upon analysis, it was found that the total number of journal articles published on the intersection of IoT, carbon emission monitoring, and residential buildings in Scopus was only 1, which was published in the year 2015. No publications were identified in 2016 and 2017. However, the number increased to 1, 4, and 7 in the years 2018, 2019, and 2020 respectively. Subsequently, there was a significant rise to 19 articles in both 2021 and 2022. The peak occurred in 2023 with 34 articles, while 10 articles were found during the first two months of 2024.

Overall, the graph illustrates a consistent growth in publications on the intersection of IoT, carbon emission monitoring and residential buildings from 2015 (1 article) to 2023 (peak of 34 articles). Many of the published articles focused on analysing the use of IoT for energy usage, energy management, and its adoption in the construction industry. Notably, a study conducted by Azizi et al., (2020) proposed managing energy efficiency and renewable energy in the residential sector through a bibliometric study. Similarly, Ba Nguyen and Cao Nguyen, (2023) explored the design and fabrication of an IoT-based smart electrical meter for residential energy management.

Despite this growing body of research, no articles were found that specifically addressed the intersection of IoT and carbon emission monitoring in residential buildings. Therefore, this study focuses on adopting IoT for carbon emission monitoring in residential buildings.

4.1.2 Leading Journals Published on Adopting IoT for Carbon Emission Monitoring

The leading journals that have published the most articles considering the intersection of IoT, carbon emission monitoring, and residential building from 2015 to 2024 were identified through the review. 'Journal of Energies' was the leading journal that published the highest number of articles (10 articles) on the intersection of IoT, carbon emission monitoring, and residential building during the period from 2015 to 2024. The 'Journal of Cleaner Production' is the second leading journal that published a high number of articles, with 8 articles. 'Building', 'Building Engineering', and 'Sustainability' (Switzerland) are other journals that have given major attention to publishing articles on the intersection of IoT, carbon emission monitoring, and residential building during the period from 2015 to 2024.

The fluctuations in leading journal publications from 2015 to 2024 are shown in Figure 2. In 2019, the leading journal for the intersection of IoT, carbon emission monitoring, and residential building is the 'Journal of Cleaner Production', with 1 publication. This number increases to 2 in 2020 and 2021 respectively. However, by 2023, it stabilises with 1 journal article published. In 2020, the 'Energies' journal begins publishing, with a dramatic increase to 4 journal articles by 2023. The 'Building' journal starts publishing in 2020, but the number of publications slightly decreases until only 1 document is published in 2022. After 2022, there are no journal publications related to the intersection of IoT, carbon emission monitoring, and residential building. Additionally, the 'Building' journal shows a slight increase in publications from 2020, with one publication in 2024 within the first two months.

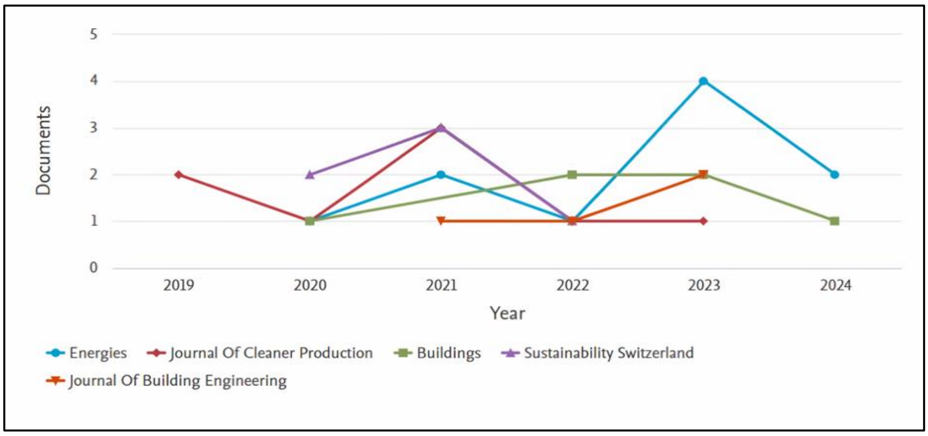

Figure 2: Evolution of leading journals

4.1.3 Leading authors on adopting IoT for carbon emission monitoring

Various scholars have contributed to the adoption of digital technology for carbon emission monitoring, such as BIM and digital twin. Figure 3 presents the leading authors who have published the most papers on IoT, carbon emission, and carbon emission monitoring for residential buildings in Scopus from 2015 to 2024. According to the analysis, the author who has published the most articles during the period from 2015 to 2024 is Oke A.E. with 3 records in Scopus. With the second-highest number of records in Scopus, 2 articles have been published by multiple authors including Aliu J., Chan A.P.C., Deng X., Fan Y.V., Klemes J.J., Lee C.T., Li H., Lu K., and Wu Z. Since there has been less focus on IoT in the context of carbon emission and carbon emission monitoring for residential buildings, the number of articles published by authors is considerably lower.

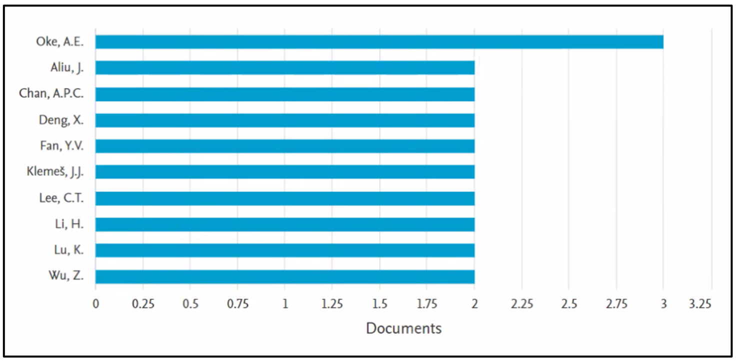

Figure 3: Leading authors analysis

The articles were further reviewed to identify the insights for adopting IoT for carbon emission monitoring of residential buildings as described below.

4.2 ADOPTING IOT FOR CARBON EMISSION AND CARBON EMISSION MONITORING AT RESIDENTIAL FACILITIES

Since IoT provides number of advantages in real-time carbon emission monitoring as mentioned earlier, many researchers have paid their attention on utilising IoT for carbon emissions monitoring in diverse sectors (Olatomiwa et al., 2023). The IoT has the potential to significantly reduce carbon emissions in residential facilities. The concept of IoT represents the energy-efficient procedures adopted by IoT to facilitate reducing energy consumption and carbon emission of existing applications and services (Oke et al., 2023). IoT can be combined with technologies like AI, machine learning, computer vision, cloud computing, nanotechnology, and big data to develop environmentally sustainable solutions (Javaid et al., 2022).

The term IoT describes a network of connected devices that are equipped with software, sensors, and other technologies to gather and share data via the internet (Oke et al., 2023). Further to the authors, IoT devices can be installed to track energy consumption, identify inefficiencies, and make recommendations for improvements in the context of carbon emission monitoring.

In the context of residential buildings, IoT is enabling buildings to reduce energy consumption and emissions. Smart buildings, which leverage IoT, manage assets, resources, and services efficiently, thereby reducing energy consumption and making buildings safer, more productive, and overall, a better place in which to live or work (Lee et al., 2015; Maksimovic, 2017). Accordingly, it appears that the use of IoT for real time carbon emissions monitoring and quantification acquires a considerable attention among researchers even though still there is a dearth in practical context. Further, according to Olatomiwa et al., (2023), IoT technology seems like a promising solution for assessing carbon emissions in houses, despite some potential challenges and ethical restrictions. Furthermore, Sarrab et al., (2020) also declare that IoT enable carbon monitoring platforms allow to determine how day-to-day activities in houses impact on carbon emissions by collect real-time data on household activities such as energy consumption and other environmental data including indoor temperature, and humidity to name a few. This facilitate individuals to identify where high carbon emissions are occurred and how to make changes in their living patterns to mitigate them (Olatomiwa et al., 2023). Further, IoT-based carbon monitoring systems can monitor energy usage, water consumption, heating and cooling patterns, and other pertinent household metrics using a combination of sensors, smart meters, and other connected devices which has an impact on total carbon emissions from houses (Lukyanov et al., 2021). Moreover, Real-time tracking of energy consumption is one of the main uses of IoT in residential carbon emission monitoring (Ming et al., 2019). Residential building equipped with smart meters are able to measure water, gas and electricity usage very precisely (Mudumbe & Abu-Mahfouz, 2015). These meters send data to a central system, where it is examined to find trends and patterns in the usage of energy (Adams et al., 2021).

Additionally, the use of IoT sensors is possible to monitor specific sources of carbon emissions in buildings (Rokonuzzaman et al., 2021). For instance, sensors can be added to HVAC systems (heating, ventilation, and air conditioning) to monitor energy use and identify problems or inefficiencies (Rashid et al., 2019). In order to monitor energy usage and carbon emissions, sensors can also be installed in appliances like dishwashers, washing machines, and refrigerators (Bansal et al., 2011). IoT devices have the potential to reduce carbon emissions by encouraging residents to make changes in their behaviour by giving them instant feedback on their energy consumption (Nižetić et al., 2020). For instance, to further reduce energy waste, IoT-enabled lighting systems and thermostats can also automatically adjust settings based on occupancy patterns (Natarajan et al., 2022). Moreover, utilise IOT as a data analytics tool to examine the gathered information and identify trends, deviations and patterns in emissions and energy use (Mohindru et al., 2020). Data visualisation tools like dashboards, graphs, and charts make it easier for building managers and residents to understand the information (Lavalle et al., 2020). When establishing IoT in residential buildings, several challenges will be encountered, such as high capital costs, a limited number of IoT experts, data accuracy and reliability issues, network connectivity problems, cyber security threats, IoT adoption and engagement, and ongoing maintenance and operation costs (Zhang et al., 2021).

4.3 A FRAMEWORK FOR IOT ENABLED CARBON EMISSION MONITORING OF RESIDENTIAL BUILDINGS

Based on the different intersections reviewed on the adopting IoT for carbon emission monitoring, a framework was developed providing important insights for future researchers in the field. The framework clearly illustrates the types of carbon emissions of residential buildings, data gathering, processing and visualising tools of IoT in a carbon emission monitoring system and potential outcomes that can be derived through the utilisation of IoT technology for carbon emissions monitoring in residential buildings. Accordingly, embodied, and operational are the main types of carbon emissions from a residential building. These emission sources can be integrated with an IoT-based carbon emission monitoring system which include data gathering, processing and visualisation tools. Subsequently, the end users can monitor the residential carbon emissions that lead to initiate carbon reduction strategies. Additionally, it facilitates several benefits as visualised in the proposed framework in Figure 4.

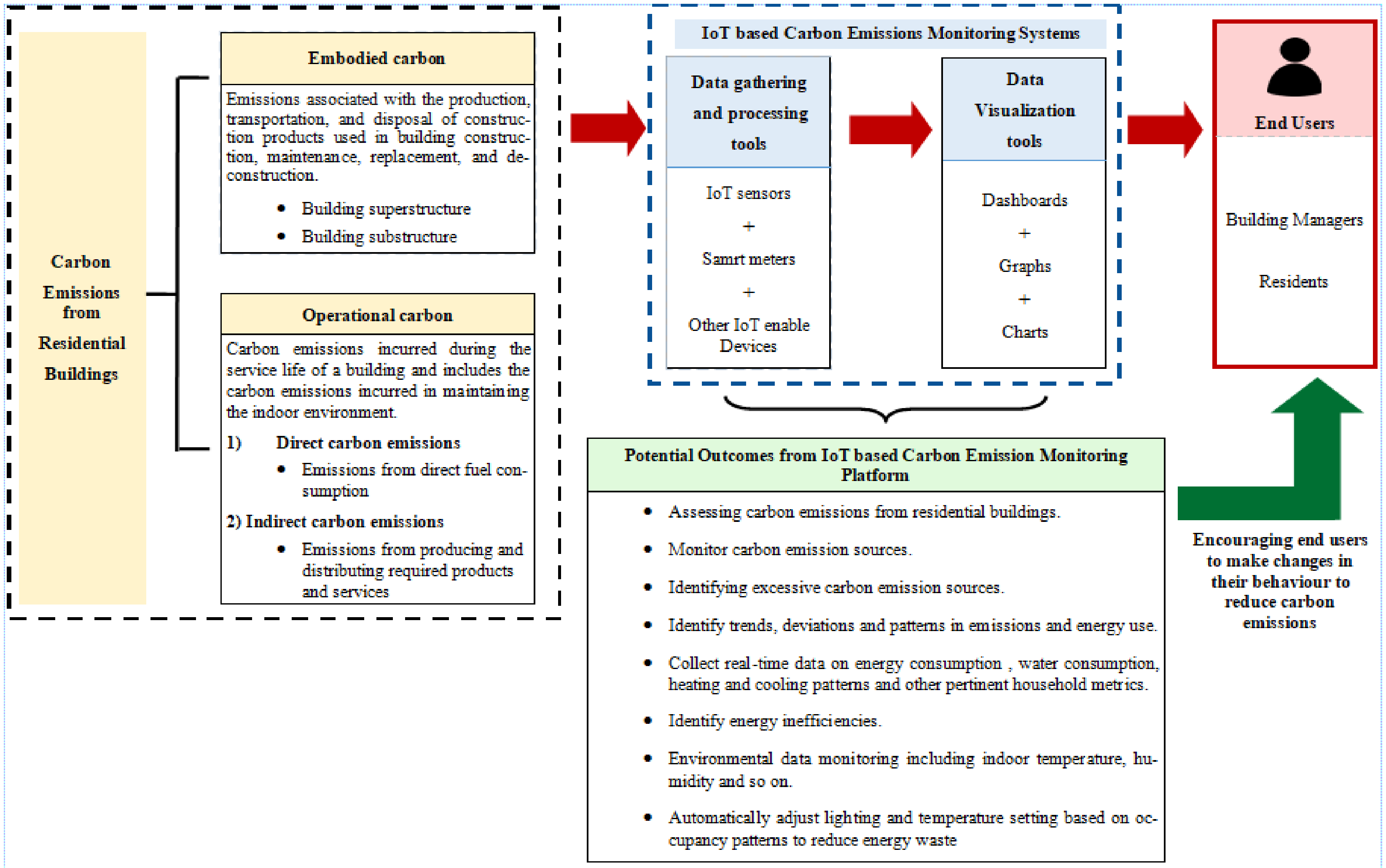

Figure 4: Framework for IoT enabled carbon emissions monitoring of residential buildings

5. CONCLUSIONS AND A WAY FORWARD

Monitoring carbon emissions at residential facilities is crucial for achieving sustainability goals. IoT solutions can be used to understand user behaviour of inhabitants through monitoring of comfort parameters in residential buildings. The use of IoT in monitoring carbon footprints has the potential to save billions of metric tons of carbon emissions. This can be achieved by automating monitoring and repetitive maintenance tasks, which can also reduce the costs of delivering service. Hence, the adoption of IoT in residential facilities can play a significant role in reducing carbon emissions and monitoring them effectively. However, it's important to note that the successful implementation of these technologies requires careful planning and consideration of various factors such as cost, privacy, and security. With such importance, this study conducted a systematic review of key literature published in the Scopus database between 2015 and 2024 to explore the adoption of carbon emission monitoring in residential buildings. The bibliometric analysis outcomes significantly contribute to identifying the number of published journals, leading journal authors, and countries active in this field. It is evident from the analysis that this is an evolving and growing area of study worldwide, with a particular focus on carbon emission monitoring. Through the analysis of existing literature, several key findings have emerged regarding the adoption of carbon emission monitoring in residential buildings. considering the intersections between IoT and carbon emissions monitoring in residential buildings, IoT enabled carbon emissions monitoring and accounting model will be developed as a way forward of this research, which may pave an important pathway for reducing carbon emissions from residential buildings while enhancing knowledge on the application of IoT for carbon emission monitoring.

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