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TECH-DRIVEN SOLUTION FOR SUSTAINABLE AFFORDABLE HOUSING: A PATH TO RESILIENT COMMUNITIES

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Abstract

This research investigates the integration of technology into sustainable, affordable housing (SAH) as a pathway to building resilient communities. The study aims to achieve three primary objectives: (1) explore research trends in the integration of technology into SAH, (2) identify solutions or challenges that various technologies in SAH can address, and (3) determine the specific research gaps in the current literature. Utilising scientometric and systematic literature review (SLR) analysis, the study highlights the key technological challenges that can be addressed to enhance energy efficiency, reduce CO_2 emissions, and achieve cost-effectiveness in affordable housing. The findings also emphasise the significant potential of smart home technologies, namely IoT-enabled sensors, smart meters, and automated energy systems, in creating more energy-efficient and environmentally sustainable homes. However, a significant research gap is identified concerning the cost and scalability of these technologies for low-income housing. The study advocates for future research to focus on developing scalable and cost-effective smart technologies for affordable housing, ultimately contributing to resilient and sustainable community development.

Keywords: Affordable house, Future research, Resilient community, Sustainable affordable housing, Technology.

1. Introduction

By 2050, the world must construct more housing than in the past 6,000 years, necessitating a shift to green and resilient building practices that meet low-income populations' needs while ensuring environmental sustainability [1]. Rapid urbanisation, housing shortages, and climate change demand innovative solutions to build sustainable, resilient communities. Technology-driven approaches are pivotal in addressing these challenges by reducing housing costs, enhancing energy efficiency, and promoting sustainability. Advancements such as prefabrication, modular construction, and 3D printing have lowered building costs, increased efficiency, and reduced material waste [2].

These scalable technologies enable faster construction of affordable housing, especially in urban areas where space and resources are constrained. Smart technologies such as Internet of Things (IoT) devices, smart grids, and renewable energy systems improve building operations, enabling efficient energy management and lowering resident operational costs [3]. These innovations reduce living costs while fostering resilient urban communities capable of withstanding environmental stresses. By minimising the environmental footprint of housing developments, cities can progress towards sustainable, self-sufficient models [4]. Such advancements are vital in emerging economies, where rapid urbanisation pressures infrastructure and resources. This article explores how technology-driven solutions for sustainable, affordable housing (SAH) contribute to building resilient communities.

2. Methods

This study sets forth three distinct objectives and integrates scientometric and SLR approaches, as summarised in Table 1.

Table 1. Summary of research objectives and methodologies.

Research Objectives		Type of analysis
1.	**To explore research trends in the integration of technology into SAH.**	Scientometric
2.	**To identify solutions or challenges that can be addressed by various technologies in SAH.**	SLR
3.	**To determine the specific research gaps relevant to this study.**	-

2.1. Identification

This study's scientometric and SLR process involved three key stages for selecting relevant papers. In the initial stage, keywords and related terms were identified through resources such as thesauruses, dictionaries, encyclopaedias, and prior studies. Once the relevant terms were established, search phrases were developed and applied in the Scopus and Mendeley databases (refer to Table 2).

Table 2. The search strings.

Data Based	Search Strings
Scopus	TITLE-ABS-KEY (technology OR technologies OR "technology integration" OR "technologies integration") AND ("affordable housing" OR "affordable home") AND (sustainability OR sustainable) AND PUBYEAR > 2019 AND PUBYEAR <2024 AND (LIMIT-TO (DOCTYPE , "ar")) AND (LIMIT-TO (LANGUAGE , "English")) AND (LIMIT-TO (SRCTYPE, "j")) AND (LIMIT-TO (PUBSTAGE, "final")) AND (LIMIT-TO (OA, "all"))
Mendeley	technology OR technologies OR "technology integration" OR "technologies integration AND Sustainable Affordable House*

2.2. Screening

The screening process involved evaluating potentially relevant research materials to determine their relevance to the research questions. The primary focus was research articles, which provided significant insights, along with other sources such as reviews, meta-syntheses, meta-analyses, books, book series, chapters, and conference papers not extensively covered in recent studies. The review was limited to English-language publications from 2019 to 2024. Duplicate entries were removed during the initial review phase. After excluding 1,509 articles, a total of 1,403 papers were shortlisted for the second round of screening based on specific inclusion and exclusion criteria (refer to Fig. 1).

2.3. Eligibility

As part of the third phase of the selection process, 1397 articles were initially shortlisted for consideration. Each was carefully reviewed, focusing on titles and key content to confirm alignment with the study's inclusion criteria and research objectives. Following this detailed review, 1382 articles were excluded for irrelevance to the study's focus, discrepancies in titles or research areas, or lack of full-text availability for data-dependent studies. Ultimately, 15 articles remained for further, in-depth analysis for this publication.

2.4. Data abstraction and analysis

2.4.1. Scientometric analysis

Information such as the publication year, author, title, journal, keywords, and citations were gathered in PlainText format. The analysis utilised mapping and clustering techniques through a VOSviewer software (version 1.6.19), with consideration of the Multidimensional Scaling (MDS) method introduced by Van Eck et al. [5]. Both approaches aim to represent the relatedness and similarity of items by positioning them in a low-dimensional space, with separation distance indicating the degree of similarity.

VOSviewer normalises co-occurrence frequencies and generates similarity metrics, such as the cosine and Jaccard indexes. It calculates association strength to quantify relationships between items, positioning them by minimising the weighted sum of squared distances. To enhance accuracy, the software applies the LinLog/modularity normalisation technique. The VOSviewer's visualisation tools uncovered patterns within the data, enabling analyses such as co-citation and keyword co-occurrence. Keyword co-occurrence analysis is particularly effective for identifying common themes and tracking the evolution of research topics. In contrast, citation analysis highlights key research questions and methodologies, aiding in assessing the historical significance of core topics within a field. The VOSviewer calculates association strength (ASij) using the following equation:

$$AS_{ij} = \frac{C_{ij}}{\omega^i \omega^j}$$

2.4.2. SLR analysis

Integrative analysis synthesised research approaches, reviewing 15 articles (Fig. 1) to identify key themes and technologies in SAH. Data collection supported theme development, with reflections and analyses documented throughout. Discrepancies in themes were addressed through discussions and design adjustments. Expert consultations validated sub-themes for clarity and relevance, ensuring domain-specific accuracy. Feedback from experts and readers further refined the study's findings and informed its final conclusions.

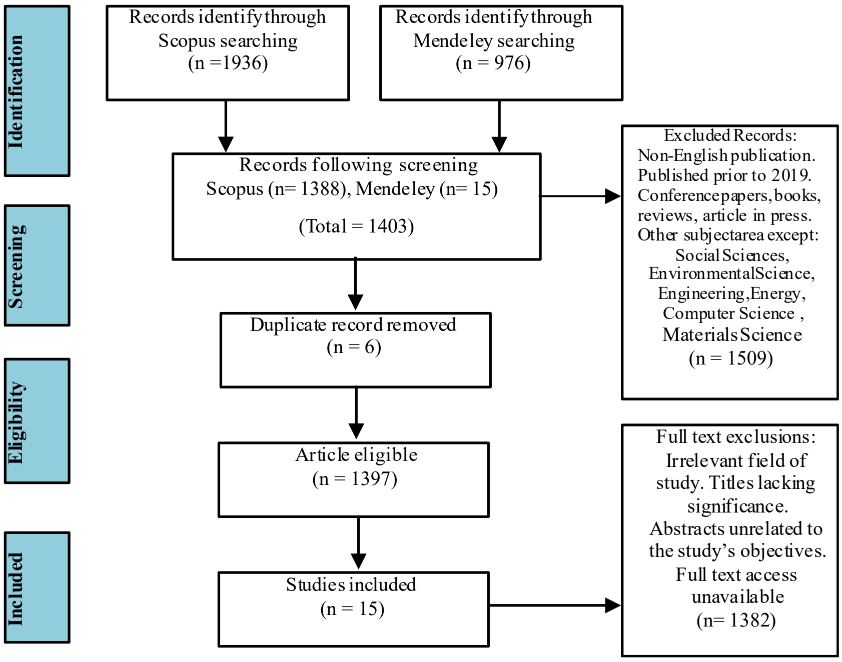

Fig. 1. Proposed search strategy flow diagram for SLR [6].

3. Results

3.1. Scientometric analysis

The VOSviewer co-occurrence map illustrates the relationships between keywords relevant to integrating technologies in SAH (refer to Fig. 2). Node size represents keyword frequency, while proximity and links indicate co-occurrence in studies. Central terms such as sustainability, housing, and energy efficiency dominate, highlighting their importance in SAH research. Clusters reveal thematic connections: urban planning, housing policy, and urbanisation form a blue cluster, emphasising socio-economic factors such as housing affordability and social policy.

The green cluster focuses on sustainable construction and materials, reflecting research on green construction and eco-friendly technologies. The red cluster, centred on energy efficiency, climate change, and building technologies, underscores the importance of energy-efficient solutions for reducing environmental impact. Lastly, the yellow cluster on waste management and recycling integrates resource management with circular economy approaches. This multidisciplinary map highlights the convergence of social, economic, and environmental factors, emphasising comprehensive strategies for sustainable housing development.

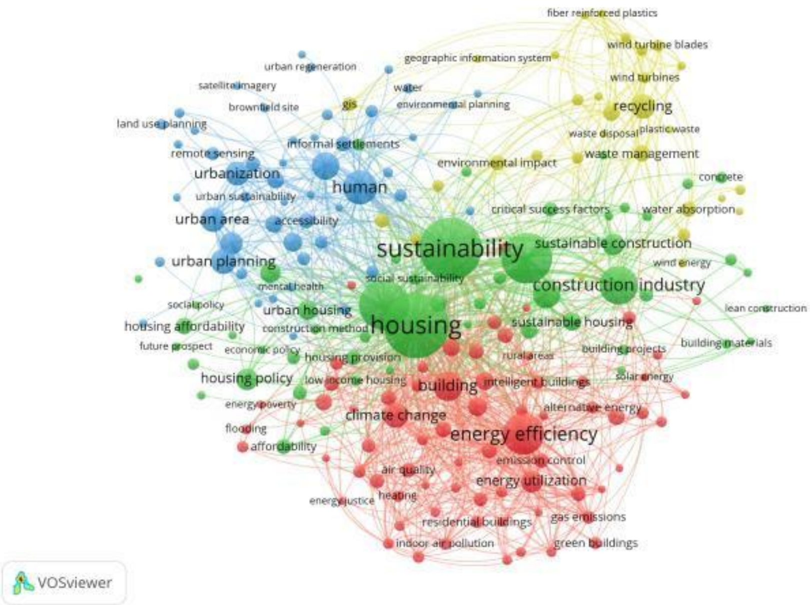

Fig. 2. Visualisation of the relationship between co-occurrence and all keywords.

The visualisation of the three-field plot in Fig. 3 highlights how research contributions are distributed geographically, thematically, and by individual expertise. The plot reveals that countries such as Australia, the United Kingdom, Malaysia, and China are significant contributors to this field, with each region focusing on distinct themes such as sustainability, affordable housing, energy efficiency, and sustainable construction. These geographical contributions are closely linked to the thematic areas being explored. The visualisation also emphasises the role of prominent researchers in shaping these themes. For instance, “Kineber AF” focuses on Building Information Modelling (BIM) and its application to sustainable construction [7].

“Oke AE” specialises in sustainable residential buildings, emphasising environmental and economic sustainability [8]. “Hamed MM” and “Rahman RA” are recognised for their contributions to energy-efficient buildings, technologies and materials [9, 10]. Similarly, “Chan APC” explores factors contributing to construction success, ensuring efficiency and sustainability in projects, while “Adabre MA” focuses on sustainable housing, particularly on long-term affordability and environmental considerations [11].

The three-field plot is a powerful tool to identify key players in the field, map research trends, and facilitate knowledge transfer. It provides a comprehensive overview of how countries, themes, and authors interact, enabling policymakers and researchers to identify potential collaborators and areas requiring further exploration. Moreover, it highlights knowledge gaps and the underrepresented regions, offering guidance for future research endeavours. By linking thematic focus to geographical and individual contributions, this visualisation underscores the need for interdisciplinary and international collaboration to address pressing global challenges in SAH.

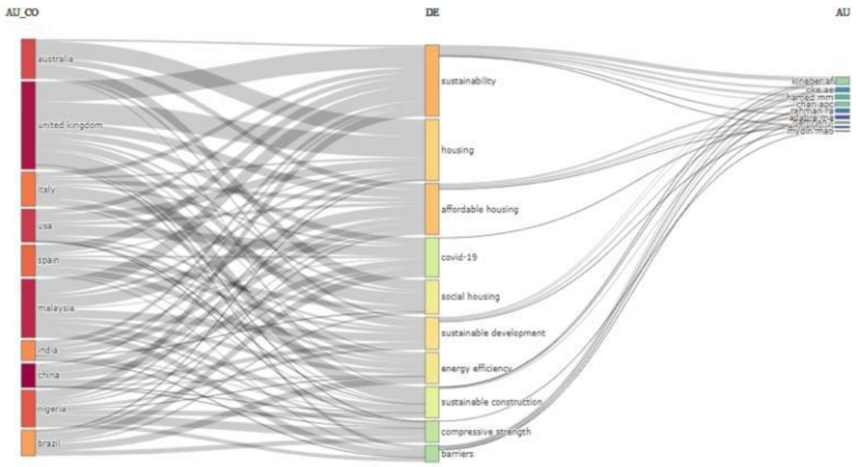

Fig. 3. Visualisation of networks of the three-field plot.

3.2. SLR analysis

The SLR highlights three major challenges that can be effectively tackled by incorporating various technologies, enhancing energy efficiency, reducing CO_2 emissions, and achieving cost-effectiveness.

3.2.1. Enhancing energy efficiency in SAH

Enhancing energy efficiency in SAH involves integrating advanced design strategies, materials, and technologies to reduce energy consumption while ensuring affordability. Passive strategies, such as optimising building orientation, natural ventilation, and insulation, minimise reliance on mechanical systems for heating and cooling. Incorporating renewable energy sources, such as solar panels and water heaters, further decreases energy demand. Energy-efficient appliances, LED lighting, and smart home systems optimise energy usage, while materials such as double-glazed windows and reflective roofing improve thermal performance [12]. These practices enhance thermal comfort and minimise environmental impacts, making housing more sustainable and resilient.

Retrofitting homes with modern insulation, energy-efficient windows, and ventilation systems significantly reduces energy intensity. Such upgrades improve thermal performance, reduce fossil fuel dependency, and lower environmental impacts, extending the lifespan and resilience of housing to address climate variability [12]. Solar energy integration offers clean, renewable energy that reduces household consumption and fossil fuel dependency, particularly in low-income communities [13]. Advanced heating technologies, such as heat pumps, efficiently use renewable energy from air, ground, or water, significantly reduce heating energy needs and operational costs [14, 15].

Simulation tools, such as Autodesk Green Building Studio, enhance energy efficiency by enabling precise modelling of energy use and assessing the impact of design changes, i.e., improved insulation and shading, without increasing costs. These tools also facilitate the incorporation of renewable technologies, such as horizontal solar panels, demonstrating their role in reducing CO_2 emissions and aligning with sustainability goals [15]. Integrating passive and active strategies, renewable energy systems and technologies such as simulation software significantly reduce energy consumption in SAH. These innovations lower operational costs, decrease environmental footprints, and promote clean energy use. By adopting these advanced practices, SAH fosters sustainable urban development and resilient housing solutions, contributing to broader sustainability objectives. Table 3 provides a summary of the article review on energy efficiency in SAH.

Table 3. Article review sample on energy efficiency in SAH.

Authors	Advantages	Technology	Solution
Mininni et al. [12]	Retrofitting buildings with new energy-efficient technologies, such as insulation and other energy-saving measures, represents a clear integration of technology aimed at reducing the energy intensity of housing.	Retrofitting buildings	Climate change
Sprague et al. [13]	The major themes revealed were the desire for and barriers to clean energy adoption. This aspect highlights the potential for integrating clean energy technologies, such as solar power or energy-efficient systems, into housing to address energy insecurity.	Solar	Energy insecurity
Lamb and Elmes [14]	Heat pumps are seen as a cleaner alternative to traditional heating systems, which typically rely on fossil fuels like natural gas. Integrating this technology will improve energy efficiency and support the UK's decarbonisation goals.	Heat pumps	Decarbonising home heating
Escribe et al. [15]	The use of energy efficiency technologies and decarbonisation strategies for reducing greenhouse gas emissions in residential buildings. Heat-pump technology reduces reliance on fossil fuels for heating homes and is key in decarbonising the residential heating sector.	Heat pumps	Decarbonising home heating

3.2.2. Reducing CO_2 emissions

The integration of technology in SAH is crucial for reducing CO_2 emissions through innovative methods. Energy-efficient materials, such as insulated concrete forms and bio-based bamboo, lower embodied carbon and enhance thermal insulation, reducing heating and cooling needs. Renewable energy systems such as solar panels and wind turbines provide clean energy, decreasing reliance on fossil fuels. Retrofitting older homes with energy-efficient windows and insulation further minimises energy consumption and carbon footprints [12]. Renewable technologies, such as rooftop solar panels, significantly reduce emissions by replacing fossil fuel-based electricity with clean energy, lowering energy costs and dependence on non-renewable sources [16, 17].

Heat pumps offer efficient alternatives to traditional heating systems by using renewable energy from air, water, or ground, further supporting decarbonisation [14, 15]. Sustainable materials, including the Composite Bamboo Shear Wall (CBSW) system in El Salvador and sawdust ash (SDA) as a partial cement replacement, reduce construction emissions and repurpose industrial by-products [18-20]. These technologies enhance affordability and sustainability in SAH, aligning with climate change targets and fostering environmentally friendly living solutions (refer Table 4). SAH demonstrates significant potential to drive long-term environmental and social benefits.

Table 4. Article review sample on the integration of technology for reducing CO_2 emissions in SAH.

Authors	Advantages	Technology	Solution
San-Martín and Elizalde et al. [17]	Rooftop solar energy, a clean and renewable technology, is increasingly adopted across residential and non-residential sectors. Its integration provides clean electricity, reducing SAH's energy costs and carbon emissions. By promoting decarbonisation and reducing reliance on fossil fuels, rooftop solar supports global climate change targets and advances a sustainable energy transition.	Rooftop solar energy	Decarbonisation & Clean Energy, Climate change
Young et al. [18]	CBSW technology in El Salvador offers a low-carbon, sustainable alternative to traditional materials like reinforced concrete. Using renewable bamboo for shear walls ensures structural integrity while significantly reducing the building's carbon footprint.	CBSW technology	Reducing the carbon footprint
Yin and Zhao [21]	The promotion of GIBMs, which are environmentally friendly and energy-efficient building materials. These materials are designed to reduce carbon emissions and energy consumption in the construction sector	GIBMs	Carbon emissions & energy consumption
Marsh et al. [22]	Focused on technical solutions to decarbonise cement and concrete. This refers to efforts to reduce the carbon emissions associated with the production of cement, which is a significant contributor to global CO_2 emissions. The technology integration here would likely include advancements in low-carbon cement production and alternative materials that can replace traditional cement in concrete.	Concrete as an Enabler of Development	Decarbonise cement & concrete/ carbon emissions

3.2.3. Achieving cost-effectiveness

Technology integration in SAH is crucial to achieving cost-effectiveness through innovative construction techniques and energy-efficient systems. These technological advancements ensure affordability while promoting sustainability. One key approach involves energy-efficient technologies, such as improved insulation, energy-efficient windows, and LED lighting systems, which reduce energy consumption for heating, cooling, and lighting. This, in turn, lowers utility bills for homeowners. Retrofitting buildings with modern insulation materials and energy systems can significantly cut operational costs while enhancing the durability and performance of structures [12]. Renewable energy sources, such as solar panels and heat pumps, further reduce SAH's long-term costs.

Solar energy systems replace traditional grid electricity, mitigating the impact of price fluctuations and lowering monthly energy bills. In Southern Africa, solar energy has reduced reliance on costly, polluting fossil fuels [17]. Similarly, heat pumps, which transfer renewable energy from air, water, or ground, provide an efficient alternative to conventional heating systems, reducing energy consumption and operational costs [14]. Prefabricated construction methods have also been integrated into SAH projects for cost savings. Prefabrication minimises on-site labour and material waste, as components are manufactured in controlled environments and assembled on-site. This reduces construction timelines, labour costs, and material waste. Innovative Prefabricated Construction Methods (IPCMs) in Southern Africa have demonstrated reductions in construction time, energy consumption, and overall project costs [23].

Smart home technologies, such as automated lighting, heating, and cooling systems, optimise energy use and improve cost savings. For instance, smart thermostats adjust indoor temperatures based on usage patterns, minimising energy consumption during low-demand periods. Additionally, sustainable building materials, such as low-carbon concrete and recycled materials, reduce the environmental footprint and resource use, leading to cost savings. When agro-waste materials, such as Shea Nut Shell Ash (SNSA), are used as partial cement replacements, material costs are lowered while structural integrity is maintained [24].

Building Information Modelling (BIM) technology enhances cost-effectiveness in SAH by enabling precise planning, digital simulations, and 3D modelling of construction projects. BIM reduces material waste, streamlines construction, and ensures timely and budget-compliant project completion. For example, BIM has optimised reinforced concrete usage, resulting in significant cost savings [25]. Transaction Costs (TCs), such as those related to split incentives and institutional transition, present barriers to energy efficiency in affordable housing. These costs can be minimised by employing energy-efficient technologies and enhancing project team competencies.

The Benefits Realisation Management (BRM) framework has been proposed to optimise client benefits, reduce unnecessary costs, and streamline energy efficiency improvements [26]. Integrating energy-efficient systems, renewable energy, prefabrication, and smart technologies in SAH significantly reduces costs and ensures long-term affordability. These innovations lower construction costs, reduce material waste and optimise energy consumption, making SAH projects sustainable and financially viable. Through these advancements, SAH can provide high-quality, affordable housing that meets economic and environmental objectives. Table 5 summarises the review of the article on achieving cost-effectiveness in SAH.

Table 5. Article review sample on achieving cost-effectiveness in SAH.

Authors	Advantages	Technology	Solution
Moghayedi and Awuzie [23]	Involves technology integration into SAH, specifically through the use of Innovative Prefabricated Construction Methods (IPCMs). The integration of IPCMs offers a solution for affordable housing delivery in Southern Africa by making housing projects more sustainable and cost-effective.	Innovative Prefabricated Construction Methods (IPCMs).	IPCMs reduce construction time, waste, & energy consumption
Mbakbaye et al. [24]	The development of efficient concrete elements in LEDCs aims to reduce construction costs and environmental impacts by optimising the use of concrete and reinforcing steel. This approach minimises material waste, lowers carbon emissions, and highlights how technology improves sustainability in housing projects	Materially efficient concrete elements	Reduce construction costs, material waste, and lower carbon emissions
De Arruda et al. [25]	Introduces a novel approach to 3D-shape parameterisation and analytical engineering methods to optimise the design of concrete elements. This approach focuses on reducing the use of concrete and reinforcing steel while maintaining structural integrity, specifically targeting Less Economically Developed Countries (LEDCs).	Materially Efficient Concrete Design	Reduce construction costs, Lowering carbon emissions

Table 5 (continue). Article review sample on achieving cost-effectiveness in SAH.

Authors	Advantages	Technology	Solution
Adetooto et al. [27]	The use of Alternative Building Technologies (ABTs), focusing on Sandbag Building Technologies (SBTs). SBTs are innovative construction technologies that use sandbags as a core building material. They offer a more affordable, sustainable, and environmentally friendly alternative to traditional building materials like brick and mortar. SBTs are praised for their fire and earthquake resistance, making them a practical and safe option in regions facing these hazards.	ABTs	Reduce construction costs
Yılmaz [28]	Focuses on using Melamine-coated Medium Density Fibreboard (MDF-LAM), a widely utilised material in construction and furniture industries due to its low cost, high strength, and dimensional stability. MDF-LAM is commonly used in various structural applications, making it relevant for sustainable housing.	Melamine-coated Medium Density Fibreboard (MDF-LAM)	Reduce construction costs, Cumulative Energy Demand (CED) Reduction

3.3. Future potential research

This section builds on the challenges and broad solutions discussed earlier, offering a wider perspective on future research directions in SAH. Future research should not solely focus on smart home technologies but consider a range of areas to comprehensively address the complex challenges of affordability, sustainability, and social equity in housing. Integrating smart home technologies, such as IoT-enabled sensors, smart meters, and automated energy systems within affordable housing for low-income communities, represents one promising pathway.

The challenge lies in making these technologies cost-effective and scalable for low-income communities, balancing the high upfront costs with long-term energy savings and better energy management [29]. By incorporating these smart systems, affordable housing can improve energy efficiency, reduce operational costs, and enhance living conditions by monitoring and controlling energy use and optimising heating, cooling, lighting, and appliances to minimise waste [30-33]. IoT-enabled sensors detect changes in the environment (e.g., temperature, humidity, occupancy) and adjust systems such as heating, ventilation, and air conditioning (HVAC) automatically [3].

By doing so, they ensure that energy is only used when needed, helping to reduce overall consumption without sacrificing comfort. Smart meters provide real-time energy consumption data, allowing residents and utility providers to monitor usage patterns. This data can inform better energy-saving habits and identify inefficiencies in energy use. Smart meters can also enable dynamic pricing, where residents pay lower rates for energy during off-peak times, leading to cost savings. Furthermore, automated energy systems can automate lighting, heating, and appliances based on usage patterns and environmental factors.

Despite the clear benefits of smart technologies, there are significant challenges to adapting these technologies to be cost-effective and scalable for low-income communities [34]. The high upfront costs of purchasing and installing smart systems often make them prohibitive for affordable housing projects. Additionally, maintenance and technical support for these systems might be less accessible in lower-income neighbourhoods, which could hinder long-term adoption and success. There is also a need to study the social dynamics surrounding the use of these technologies in low-income communities. Many residents may not be familiar with how to operate or fully benefit from smart home systems, leading to underutilisation. Hence, future research should address the education and training necessary to maximise the benefits of these systems for residents.

Another area for future research is the scalability of these smart technologies in affordable housing developments. Research should explore the possibility of community-wide solutions, such as installing shared energy management systems across housing complexes, where the cost is distributed among multiple households. This could be particularly beneficial in apartment buildings or multi-family housing units.

Smart technologies represent a promising pathway to improving energy efficiency in affordable housing, but their potential has yet to be fully realised in low-income communities. Future research should focus on developing cost-effective and scalable solutions that address the unique challenges of these communities, such as high upfront costs, accessibility, and user education [35]. With the proper support and innovation, smart home technologies could play a pivotal role in making affordable housing more energy-efficient, sustainable, and cost-effective in the long run.

The conceptual framework proposed for determining SAH is built around three key factors. The first factor, Housing Affordability, is adopted from [36, 37], which applies the Residual Income Model. This model emphasises the relationship between three core components: household income, household expenditure, and house cost. The second factor, Technology Integration, represents Research Gap 1 in the literature. This gap highlights the need to explore the role of modern technologies in making housing more sustainable and affordable [38].

Technologies such as IoT-enabled sensors, smart meters, and automated energy systems are being introduced to improve energy efficiency and reduce home costs. These technologies can monitor and manage energy usage more effectively, lowering the overall operational costs of a household and thus contributing to long-term housing affordability [39, 40]. However, existing research has not fully explored integrating such technologies into affordable housing. The third factor, Community Challenges, represents Research Gap 2. It focuses on the social barriers to achieving SAH. Key community challenges include high upfront costs associated with new technologies, accessibility to these technologies for lower-income groups, and user education [38].

These challenges suggest that while technological advancements can contribute to affordability, issues related to the cost of implementation, access to necessary resources, and a lack of knowledge or training in using these technologies hinder their widespread adoption. Addressing these gaps will be crucial in ensuring that technology-based solutions are both accessible and beneficial to the broader community, particularly in the context of affordable housing. A conceptual framework for the research gap is illustrated in Fig. 4.

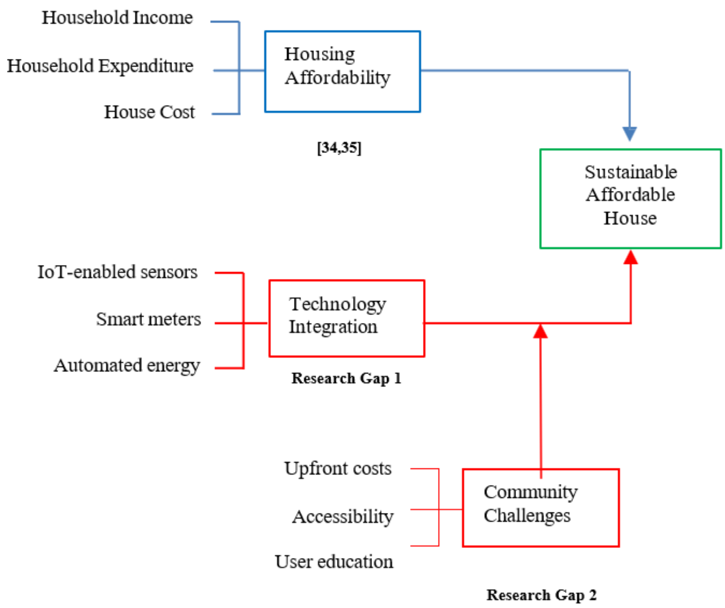

Fig. 4. Propose a conceptual framework for the research gap.

4. Conclusion

This research explores the integration of technology into SAH as a strategy to build resilient communities. The study's key objectives are to examine research trends, identify technological solutions for SAH challenges, and uncover research gaps. Through a scientometric and systematic literature review analysis, the research highlights the potential of innovative technologies to enhance energy efficiency, reduce CO_2 emissions, and improve cost-effectiveness in affordable housing. The study advocates for future research to focus on developing affordable and scalable smart technologies that can be easily implemented in SAH projects. Overall, the integrating technology in SAH offers promising solutions to energy and environmental challenges; thus, addressing cost barriers is critical to ensuring widespread accessibility and long-term sustainability for low-income communities.

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