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Original
Behavioural Modelling for Sustainability in Smart Homes / Ardito, L.. - ELETTRONICO. - (2024), pp. 1-11. (ARES 2024: The 19th International Conference on Availability, Reliability and Security Vienna (AUT) 30 July 2024- 2 August 2024) [10.1145/3664476.3670946].

Availability:
This version is available at: 11583/2991672 since: 2024-08-12T13:48:21Z

Publisher:
Association for Computing Machinery

Published
DOI:10.1145/3664476.3670946

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17 October 2026

Behavioural Modelling for Sustainability in Smart Homes

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ABSTRACT

This paper explores the critical aspects of behavioural modelling for sustainability in smart homes, emphasising the integration of advanced technologies to enhance energy efficiency, convenience, security, and overall quality of life. Smart homes utilise interconnected devices and sensors to collect detailed data on residents' behaviours, energy usage, and environmental conditions. Predictive analytics, leveraging machine learning algorithms and data mining techniques, optimises home systems by anticipating residents' needs and promoting efficient energy use.

Behavioural interventions, such as real-time feedback, automation, incentives, and nudges, influence residents' actions toward more sustainable practices.

However, privacy concerns about data collection, unauthorised access, and data misuse present challenges. Addressing these issues through robust security measures, transparent policies, and user education is crucial. Additionally, promoting adoption and user engagement requires highlighting the perceived benefits, affordability, ease of use, and trusted brands while overcoming barriers like privacy concerns, technological complexity, and lack of awareness.

Practical strategies to enhance adoption and engagement include education campaigns, financial incentives, user-friendly design, robust customer support, and community building. By addressing these factors, smart home technologies can become integral to modern living, contributing to a more sustainable and efficient future.

This paper aims to provide a comprehensive overview of the current and future directions in smart home sustainability, highlighting the interplay between technology, policy, and user engagement to shape research directions and foster a sustainable and efficient future.

CCS CONCEPTS

• **Computing methodologies** → **Machine learning**; • **Theory of computation** → *Unsupervised learning and clustering*; **Reinforcement learning**; • **Security and privacy** → **Social aspects of security and privacy**; **Data anonymization and sanitization**; • **Computer systems organization** → **Sensor networks**; *Embedded systems*; • **Information systems** → *Data mining*; *Decision support systems.*

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ARES 2024, July 30–August 02, 2024, Vienna, Austria
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ACM ISBN 979-8-4007-1718-5/24/07
https://doi.org/10.1145/3664476.3670946

KEYWORDS

Smart homes; Sustainability; Behavioural modelling; Energy efficiency; Predictive analytics; Data privacy

ACM Reference Format:
Luca Ardito. 2024. Behavioural Modelling for Sustainability in Smart Homes. In *The 19th International Conference on Availability, Reliability and Security (ARES 2024), July 30–August 02, 2024, Vienna, Austria.* ACM, New York, NY, USA, 11 pages. https://doi.org/10.1145/3664476.3670946

1 INTRODUCTION

Sustainability has become a paramount concern in modern society, particularly concerning energy consumption and environmental impact. Integrating smart technologies in homes offers a promising avenue for enhancing sustainability. This paper explores the concept of behavioural modelling in smart homes and its potential to promote sustainable practices among residents. Smart homes integrate various technologies to create an intelligent, responsive living environment that enhances convenience, efficiency, security, and comfort. As these technologies continue to evolve, the capabilities and benefits of smart homes are expected to expand, further transforming how people interact with their living spaces.

Smart homes, also known as intelligent homes or connected homes, refer to residences equipped with advanced automation systems and interconnected devices that can be controlled remotely or automatically to enhance the living experience. These systems and devices are designed to increase convenience, improve energy efficiency, bolster security, and provide greater comfort to residents.

The core components of smart homes encompass a variety of interconnected technologies designed to enhance convenience, efficiency, and security. Smart devices and appliances are integral, with everyday household items enhanced by internet connectivity and advanced features, such as smart refrigerators tracking food inventory, smart ovens preheating remotely, and smart washing machines controllable via smartphone apps. Sensors and actuators are also crucial, gathering data about the home's environment and the occupants' activities. Standard sensors include motion detectors, temperature, humidity, and light sensors. At the same time, actuators perform actions like adjusting lighting or opening and closing windows based on signals from the control system. At the heart of a smart home is the central hub or control system, which aggregates data from various devices and sensors, allowing homeowners to monitor and control their smart home systems through a smartphone app or dedicated device, such as Amazon Echo, Google Home, or Apple HomeKit. Connectivity is vital to the seamless operation of smart homes, with robust options like Wi-Fi, Bluetooth, Zigbee, and Z-Wave technologies enabling devices to communicate and function cohesively.

The functionalities of smart homes are diverse and cater to various aspects of modern living, enhancing convenience, efficiency, and security. Home automation allows smart home systems to perform tasks automatically based on pre-set rules or learned behaviours, such as programming lights to turn on at sunset or adjusting thermostats based on occupancy patterns. Remote control and monitoring capabilities enable homeowners to manage home systems from anywhere using a smartphone or tablet, allowing them to lock or unlock doors, adjust thermostats, and view security camera feeds. In terms of energy management, smart homes contribute to sustainability by using smart thermostats that learn residents' schedules and adjust heating and cooling to minimise energy use, as well as smart plugs and energy monitoring systems that track electricity usage and provide insights for energy savings. Security and surveillance are bolstered by smart home security systems, including smart locks, doorbell cameras, motion sensors, and alarm systems, offering real-time alerts and remote monitoring. Integrated entertainment systems provide a seamless experience for managing centralised audio and video equipment, with smart TVs, speakers, and streaming devices controllable through a single interface. Additionally, health and wellness functionalities in smart homes include devices like smart beds that monitor sleep patterns, air quality monitors to ensure a healthy environment, and smart exercise equipment that tracks fitness goals, contributing to overall well-being.

Examples of smart home technologies illustrate the breadth and sophistication of these systems in enhancing convenience, security, and energy efficiency. Smart lighting systems, such as Philips Hue, allow users to control the brightness and colour of their lights via a mobile app or voice commands. They can also be programmed to create different lighting scenes for various occasions and times of the day. Smart thermostats, like the Nest Learning Thermostat, learn users' habits and automatically adjust heating and cooling settings to save energy while providing insights into energy usage and tips for further conservation. Comprehensive smart security systems, such as those offered by Ring or Arlo, include video doorbells, security cameras, and motion detectors that alert homeowners' smartphones when unusual activity is detected, enhancing home security. Voice assistants like Amazon Alexa, Google Assistant, and Apple Siri can manage smart home devices, provide information, and automate daily tasks through voice commands, adding a layer of convenience and control to the smart home ecosystem.

In this paper, we explore the integration of behavioural modelling and advanced technologies in smart homes to enhance energy efficiency, convenience, and sustainability.

The remainder of this paper is organised as follows: Section 2 provides a review of the background and related work in the smart home technologies landscape, focusing on energy management, user engagement, privacy and security, and future trends. Section 3 deals with the concept of sustainability and proposes different metrics and techniques for assessing it in the context of smart homes. Section 4 delves into exploring behavioural modelling in smart homes, including data collection, predictive analytics, and behavioural interventions. Section 5 discusses privacy concerns related to smart home technologies, including data collection practices, potential risks, regulatory frameworks, and mitigation strategies. Finally, Section 6 concludes the paper, outlining future research directions and the potential impact of smart home technologies on sustainability and quality of life.

2 BACKGROUND AND RELATED WORK

The body of research on smart home technologies is extensive, with significant contributions focusing on energy management, user engagement, privacy and security, and future trends. This section synthesises critical findings from the literature, offering a comprehensive overview of the current state of research in these areas.

Energy management in smart homes has been a critical focus area, aiming to optimise energy consumption and integrate renewable energy sources [7]. Li et al. (2022) conducted a systematic scientometric analysis of smart home research over two decades, revealing clusters such as ICT for home automation, AI for home automation, and domestic energy management [13]. They found that IoT is pivotal in achieving fully functional smart homes by enhancing interconnectedness among devices, which is crucial for energy management.

Yang and Wang (2013) developed a multi-agent system for building energy and comfort management based on occupant behaviours. Their study demonstrated the capability of intelligent buildings to interact with occupants to optimise energy use and enhance comfort [25]. Similarly, Magara et al. (2024) highlighted the importance of privacy and security in deploying IoT to improve energy management in smart homes [15]. Molla et al. (2018) reviewed optimisation techniques for smart home energy management systems, emphasising the role of controllers in minimising energy utilisation and reducing the peak-to-average power ratio [18].

Chen et al. (2016) proposed an optimal power management method for plug-in hybrid electric vehicles, using particle swarm optimisation to optimise energy use within smart homes [4]. Geng et al. (2016) introduced an IoT-based energy management system for households, employing a bacterial colony chemotaxis algorithm to find optimal scheduling schemes, which supports integrating renewable energy sources like solar panels and wind turbines [8]. Mahmood et al. (2016) [16] developed a realistic scheduling mechanism for smart homes, utilising binary particle swarm optimisation to enhance appliance utility and reduce user frustration.

Ahmed et al. (2023) emphasised the need for robust energy management strategies in smart homes and cities to enhance sustainability and efficiency. Their comprehensive review discussed the integration of ICT and IoT in managing energy resources, reducing waste, and promoting sustainable development [1].

User engagement and acceptance are crucial for successfully implementing smart home technologies [20]. Li et al. (2022) emphasised the growing research focused on user-centred design to enhance lifestyle and increase smart home adoption rates [12]. Shouran et al. (2019) identified key factors influencing user engagement in IoT-based smart homes, such as convenience, cost savings, and enhanced security [26]. Magara et al. (2024) also addressed the negative perceptions among Asian elderly users towards smart homes, underscoring the need to tackle these issues to improve adoption [15].

Allameh et al. (2012) explored the role of smart homes in smart real estate, focusing on user-centric design to boost acceptance [2].

Their findings indicated that simplifying user interfaces and providing financial incentives for energy-efficient technologies could significantly enhance user engagement. Similarly, the study on embracing the smart-home revolution in Asia by elderly users highlighted the importance of designing user-friendly interfaces and addressing privacy concerns to increase acceptance [19].

Privacy and security are paramount in smart homes due to the extensive data collection. Ziegeldorf et al. (2013) reviewed the privacy threats and challenges in IoT, proposing robust encryption and security protocols to safeguard user data [27]. Magara et al. (2024) discussed various strategies to mitigate privacy risks, emphasising the importance of data security in IoT-based smart homes [15]. Shouran et al. (2019) proposed a comprehensive model for privacy and security, highlighting the necessity for robust measures to protect sensitive data [26]. Sicari et al. (2015) explore the critical aspects of security, privacy, and trust in the Internet of Things (IoT) in [22]. The authors highlight the primary challenges and propose a framework to address these issues, emphasizing the importance of robust security protocols and privacy measures to foster trust in IoT applications.

Cirillo et al. (2023) in [5] focused on evaluating privacy and security needs in IoT-enabled smart homes, mainly through flexible voice assistants. They proposed a framework for enhancing the privacy and security of smart home environments by integrating advanced access control mechanisms and ensuring secure data management.

Innovations and future trends in smart home technologies focus on enhancing energy efficiency and integrating renewable energy sources. Li et al. (2022) identified emerging trends in smart home research, such as the increasing importance of IoT, AI, and renewable energy integration [13]. Their analysis highlighted the role of advanced technologies in driving the evolution of smart homes. Ahmed et al. (2023) also discussed the future trends in smart homes and cities, emphasising the role of advanced technologies in promoting sustainable urban development [1].

3 SUSTAINABILITY IN SMART HOMES

Integrating smart technologies in homes significantly contributes to sustainability, addressing pressing environmental challenges and enhancing quality of life. This section explores the multifaceted importance of sustainability in smart homes, including energy efficiency, environmental impact, economic benefits, improved quality of life, and contributing to global sustainability goals.

By leveraging advanced technologies, smart homes can optimise energy and resource use, fostering a more sustainable future. As innovations continue to emerge, the potential for smart homes to drive sustainability will only grow, making them an essential component of modern, eco-friendly living.

Smart homes significantly enhance energy efficiency through optimised energy consumption, real-time monitoring, and automated systems. These homes are designed to optimise energy usage with intelligent control systems that adjust settings based on the residents' schedules and preferences. For instance, smart thermostats learn residents' routines, automatically adjusting heating and cooling to prevent energy wastage when the home is unoccupied. Real-time monitoring devices provide valuable data on energy consumption, enabling residents to identify energy-intensive appliances and implement corrective measures, thus fostering more conscious energy use habits. Automated systems enhance efficiency; smart lighting systems adjust based on natural availability and occupancy, reducing unnecessary electricity usage. Smart plugs and power strips can also cut power to idle devices, preventing phantom energy consumption and ensuring that energy is used only when needed. Smart homes have a substantial positive environmental impact, primarily by reducing carbon footprints, conserving resources, and using sustainable materials and construction practices. By enhancing energy efficiency, smart homes significantly reduce greenhouse gas emissions. Lower energy consumption decreases the demand for electricity generation. Smart water management systems, such as smart irrigation controllers, contribute to resource conservation by ensuring efficient water use. These systems adjust watering schedules based on real-time weather conditions and soil moisture levels, thus minimising water wastage and promoting sustainable water practices. Additionally, smart homes often incorporate sustainable building practices, with many homes using eco-friendly materials and designs that maximise natural lighting and ventilation. This reduces the energy needed for heating, cooling, and lighting and supports broader environmental sustainability goals.

Smart homes contribute significantly to global sustainability goals by aligning with the United Nations Sustainable Development Goals (SDGs) and benefitting the community and the electrical grid. They directly support SDG 7 (Affordable and Clean Energy), SDG 11 (Sustainable Cities and Communities), and SDG 13 (Climate Action) by promoting energy efficiency and minimising environmental impact. Smart homes help reduce greenhouse gas emissions and reliance on fossil fuels through optimised energy consumption and integrating renewable energy sources, supporting global efforts to combat climate change.

Furthermore, smart homes substantially benefit the broader community and electrical grid. Participation in demand response programs allows smart homes to adjust their energy usage during peak times, thereby reducing the strain on the grid and helping to prevent blackouts. This collective effort not only enhances grid stability but also contributes to the creation of more resilient and sustainable communities [3]. By reducing overall energy demand and supporting grid management, smart homes play a crucial role in fostering a more sustainable and efficient energy ecosystem, benefiting individual households and society.

Smart homes offer substantial economic benefits, primarily through reduced utility bills, increased property value, and government incentives and rebate eligibility. One of the most immediate advantages is the significant reduction in utility bills. Smart homes help residents save on electricity, heating, cooling, and water costs by optimising energy and water usage. These savings accumulate over time, providing a clear financial incentive for adopting smart home technologies. Additionally, homes equipped with smart technologies often command higher market values. As prospective buyers increasingly prioritise energy-efficient and sustainable homes, the presence of advanced smart systems enhances the attractiveness and marketability of these properties, reflecting their long-term savings and environmental benefits. Furthermore, many governments offer financial incentives and rebates for installing energy-efficient

appliances and systems. Smart homes, with their advanced energy management capabilities, frequently qualify for these benefits, making the initial investment more affordable and further boosting their economic appeal.

Smart homes significantly improve quality of life by enhancing comfort and convenience, promoting health and well-being, and bolstering safety and security. Sustainable smart homes offer a high degree of comfort and convenience through automated systems that maintain optimal home environments with minimal effort from residents. For instance, smart thermostats consistently regulate temperature to comfortable levels, while smart lighting adjusts to create the perfect ambience for any activity or time of day.

Health and well-being are also prioritised in smart homes. Air quality monitors detect pollutants and allergens, triggering air purifiers to ensure the air remains clean and safe to breathe. Smart water systems provide safe and clean water, and precise temperature and humidity controls maintain indoor conditions that support overall health.

Additionally, smart home security systems enhance safety and security by incorporating features such as cameras, motion detectors, and smart locks. These systems offer real-time alerts and remote monitoring capabilities, allowing residents to monitor their homes from anywhere. This added layer of security protects against intrusions and provides peace of mind, contributing to a higher overall quality of life for residents.

Advances in artificial intelligence (AI) and machine learning are set to revolutionise smart home systems. These technologies enable smart homes to learn from residents' behaviours and predict energy usage patterns accurately. AI-driven systems can optimise heating, cooling, lighting, and appliance use in real time, leading to substantial energy savings. Machine learning algorithms continually refine these predictions and adjustments, ensuring energy management becomes increasingly efficient. This capability enhances sustainability and improves the overall user experience by providing a more responsive and adaptive living environment.

The future of smart homes is marked by several innovations and trends that promise further to enhance their efficiency, sustainability, and overall functionality.

3.1 Sustainability Metrics in Smart Homes

In the context of smart homes, sustainability metrics are essential for evaluating and guiding smart home technologies' environmental, economic, and social performance. These metrics provide a quantifiable means to assess smart home systems' efficiency, effectiveness, and impact in promoting sustainable living. By defining and utilising sustainability metrics, homeowners, developers, and policymakers can better understand the benefits of smart home technologies and identify areas for improvement. This section introduces and defines vital sustainability metrics achievable in smart homes.

Environmental Metrics:

- Energy Efficiency: Measures the reduction in energy consumption due to the implementation of smart technologies. This can be assessed through metrics such as kilowatt-hours (kWh) saved, percentage reduction in energy use, and improvements in the energy efficiency ratio (EER).
- Carbon Footprint: Quantifies the reduction in greenhouse gas emissions achieved by smart home technologies. This can be measured in terms of CO2 equivalents (CO2e) avoided.
- Water Usage Efficiency: Evaluate the reduction in water consumption through smart water management systems, such as smart irrigation controllers and water-saving fixtures. Metrics include litres of water saved and percentage reduction in water use.

Economic Metrics:

- Cost Savings: Assesses the financial benefits of reduced utility bills and operational costs due to energy-efficient and automated systems. This can be measured in terms of dollars saved per year or percentage reduction in utility bills.
- Return on Investment (ROI): Evaluate the economic return from investing in smart home technologies. This can be calculated as the net benefits (savings) ratio to the initial investment cost.
- Property Value Increase: Measures the appreciation in property value attributed to integrating smart home technologies. This can be assessed through market valuation studies and comparative analysis.

Social Metrics:

- Comfort and Convenience: Evaluate improvements in the quality of life due to smart home technologies. This can be measured through user satisfaction surveys, the number of automated tasks, and time saved on household activities.
- Health and Well-being: Assesses the impact of smart technologies on residents' health. Metrics include improving indoor air quality (measured by pollutant levels), reductions in humidity-related issues, and the effectiveness of health monitoring devices.
- Safety and Security: Measures enhancements in home security and safety. This can be assessed through the number of security incidents prevented, user perception surveys, and the reliability of security systems.

3.2 A conceptual framework for managing Sustainability Metrics in the Smart Home

Implementing and tracking sustainability metrics in smart homes requires a structured approach encompassing data collection, analysis, reporting, and continuous improvement. Initially, it is essential to utilise smart meters, sensors, and IoT devices to gather real-time data on energy consumption, water usage, indoor environmental quality, and security incidents. User interfaces such as mobile apps and dashboards should be implemented to facilitate residents' data entry and monitoring. Once data is collected, applying data analytics and machine learning techniques to process and analyse it can help identify patterns and areas for improvement. Based on historical data, predictive analytics can forecast potential energy savings and environmental impacts.

For reporting and feedback, developing comprehensive reports that present sustainability metrics in an understandable format using graphs, charts, and visualisations is crucial. Providing feedback to residents and stakeholders, highlighting achievements, and

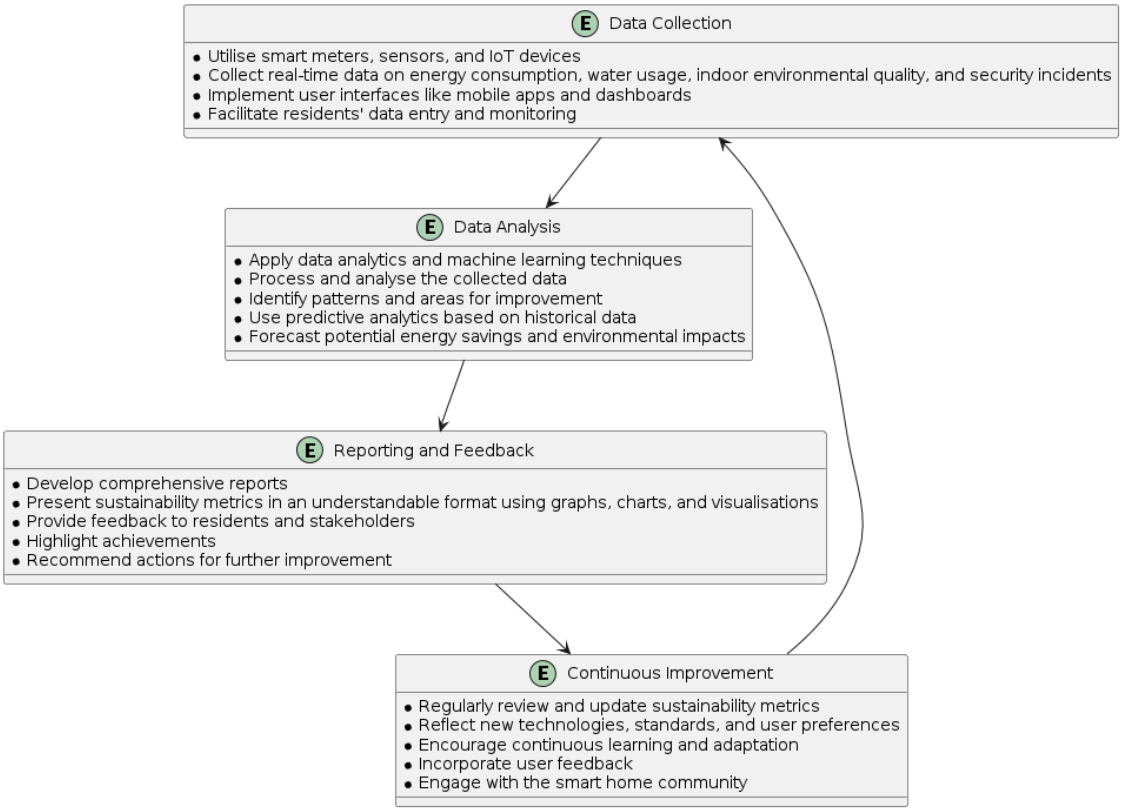

Figure 1: Conceptual Framework for Managing Sustainability Metrics in the Smart Home

recommending actions for further improvement can enhance engagement and drive better outcomes. Continuous improvement involves regularly reviewing and updating the sustainability metrics to reflect new technologies, standards, and user preferences. Encouraging continuous learning and adaptation by incorporating user feedback and engaging with the smart home community ensures that the system remains relevant and effective over time.

Figure 1 shows a conceptual framework for managing Sustainability Metrics in the Smart Home.

4 BEHAVIOURAL MODELLING IN SMART HOMES

Behavioural modelling in the context of smart homes involves using data-driven techniques to analyse and predict the behaviours and patterns of residents. This approach allows for customising home environments to enhance comfort, efficiency, and sustainability. Here, we delve deeper into the critical aspects of behavioural modelling, including data collection, predictive analytics, and behavioural interventions.

Behavioural modelling in smart homes leverages advanced data collection and predictive analytics to understand and influence residents' behaviours. This approach enhances comfort and convenience and promotes sustainability by optimising energy usage and encouraging eco-friendly practices. As smart home technologies evolve, the potential for behavioural modelling to drive sustainable living will expand, making it a cornerstone of modern, intelligent homes.

4.1 Data Collection

The foundation of behavioural modelling is the collection of accurate and comprehensive data. In smart homes, this data is gathered through various interconnected devices and sensors, each providing valuable insights into the residents' habits and routines. By gathering comprehensive and accurate data on energy usage, occupancy, appliance use, and environmental conditions, smart home systems can optimise their performance to enhance sustainability, comfort, and convenience. Despite challenges related to privacy, security, and data integration, the benefits of effective data collection are substantial, making it a foundational element of modern smart home technology.

4.1.1 Definitive analysis. Smart homes collect various data types to optimise energy use, improve comfort, and enhance security. Energy usage data is a primary category, where smart meters provide real-time information on electricity consumption, helping to identify peak usage times and the impact of specific devices. Similarly, smart meters for gas and water track real-time consumption, offering crucial insights into heating systems, hot water, and irrigation. Occupancy data is gathered through motion sensors, which detect movement within the home, informing the automation of lighting,

heating, and cooling systems. Door and window sensors provide data on the opening and closing of these entry points, helping to track the comings and goings of residents and identify potential energy loss. Smart locks add another layer of occupancy data by logging when and by whom the home is accessed. Appliance usage data is collected from smart appliances such as refrigerators, ovens, washing machines, and dishwashers, which log their usage patterns, crucial for energy management and maintenance schedules. Additionally, smart plugs and power strips monitor the energy consumption of plugged-in devices, providing granular data that can identify opportunities to reduce waste. Environmental data, which includes temperature, humidity, light, and air quality sensors, plays a significant role in maintaining a comfortable and healthy living environment. Temperature sensors optimise HVAC performance; humidity sensors prevent mould growth; light sensors ensure efficient use of natural and artificial lighting; and air quality sensors detect pollutants and allergens, triggering air purifiers or ventilation systems as needed.

4.1.2 Data Collection Methods. Smart homes utilise various data collection methods to gather comprehensive information that enhances their functionality and efficiency. Embedded sensors are integral, with devices like the Nest Learning Thermostat incorporating built-in sensors to monitor temperature, humidity, and occupancy, thus providing extensive data for energy management. Similarly, smart lighting systems like Philips Hue use sensors to detect ambient light levels and occupancy, enabling automatic lighting adjustments. Wearable devices also play a crucial role in data collection. Smartwatches and fitness trackers offer additional insights into residents' activities, sleep patterns, and health metrics, contributing to a holistic understanding of behaviour and needs. Health monitors, which track heart rate, stress levels, and other health indicators, provide valuable data that can inform adjustments in the smart home to enhance overall well-being. Manual input from residents is another important method of data collection. By manually setting their preferences for temperature, lighting, and other settings, residents allow the smart home system to learn and adapt to these preferences over time. Additionally, some systems enable residents to set schedules for appliance use, heating, and cooling, which the smart home can use to optimise energy consumption. These diverse data collection methods ensure that smart homes can operate efficiently, meet the specific needs of their residents, and contribute to a more sustainable living environment.

4.1.3 Challenges in Data Collection. Data privacy and security are paramount in smart home systems, as collecting detailed data about residents' behaviours and home environments raises significant privacy concerns. This data must be anonymised and securely stored to protect residents' privacy. Robust encryption and security protocols are necessary to prevent unauthorised access to sensitive data, safeguarding the system against cyber threats.

The accuracy and reliability of the data collected are also crucial for effective data-driven decision-making. The accuracy of sensors directly impacts the quality of the data collected; therefore, regular calibration and maintenance are essential to ensure reliable performance. Furthermore, integrating data from various sources and devices can be challenging. Ensuring compatibility and effective communication between all devices is vital for a comprehensive understanding of the home environment.

User engagement is another critical factor for the success of data collection efforts in smart homes. Active participation from residents is necessary to collect meaningful data, as their engagement with the system significantly influences the quality and quantity of the data gathered. The ease of use of smart home systems plays a significant role in encouraging this participation. User-friendly interfaces that make it easy for residents to input data and adjust settings are essential, as complex interfaces can discourage use and reduce the effectiveness of data collection.

4.1.4 Benefits of Effective Data Collection. Accurate data collection in smart home systems enables the delivery of highly personalised experiences by adjusting settings to meet residents' specific needs and preferences. This detailed data on energy consumption and usage patterns facilitates precise energy management, resulting in significant energy savings and reduced utility bills. By understanding residents' behaviours and preferences, smart home systems can enhance comfort and convenience, creating a more enjoyable living environment. Additionally, data from security devices is crucial in protecting the home from intrusions and other security threats, providing residents with peace of mind. Environmental and health data also allow smart home systems to foster healthier living conditions, improving overall well-being.

4.2 Predictive Analytics

Predictive analytics is a powerful tool in smart homes, enabling the anticipation of resident behaviours and optimisation of home systems for enhanced efficiency, comfort, and security [24]. By leveraging advanced machine learning algorithms, data mining techniques, and statistical analysis, smart homes can provide personalised experiences and contribute significantly to sustainability goals. However, data quality, privacy, system integration, and user acceptance must be addressed to realise the potential of predictive analytics in smart homes fully. As technology advances, the capabilities and benefits of predictive analytics will continue to grow, making it an integral part of the future of smart living.

4.2.1 Technologies Involved. Machine learning algorithms, data mining, and statistical analysis are essential tools for optimizing smart home systems [11]. Supervised learning involves training algorithms on labelled data sets to predict outcomes based on new input data, such as forecasting energy usage from historical consumption patterns and current environmental conditions [9]. Unsupervised learning algorithms [14], on the other hand, identify patterns and relationships within unlabelled data, enabling the discovery of usage patterns and grouping similar behaviours without prior knowledge. Reinforcement learning focuses on decision-making and reward-based learning, which can optimise HVAC systems by learning the most energy-efficient ways to maintain comfort levels.

Data mining techniques like clustering and association rule learning play a crucial role in managing smart home data. Clustering groups similar data points together, helping to identify usage patterns among residents or appliances [6]. Association rule learning identifies relationships between variables in large data sets, such as

finding associations between high energy usage and specific times of the day or certain activities.

Statistical analysis methods, including regression analysis and time series analysis, are also vital. Regression models help understand relationships between variables and predict future values, enabling predictions of future energy consumption based on past usage and factors like weather conditions [17]. Time series analysis examines data points collected at specific intervals, which is beneficial for forecasting trends in energy usage, occupancy [21], and environmental conditions over time.

4.2.2 Applications of Predictive Analytics in Smart Homes. Predictive analytics in smart homes offer many applications that significantly enhance energy management, HVAC optimisation, appliance usage, security, and personalisation [10]. In energy management, predictive analytics can forecast periods of high and low energy demand, enabling residents to take advantage of dynamic pricing models by shifting energy-intensive tasks to off-peak hours, thereby achieving cost savings. Additionally, load forecasting helps optimise energy distribution and prevent overloads, ensuring efficient energy use and stability of the smart grid. For HVAC optimisation, predictive models analyse historical temperature data and current environmental conditions to adjust HVAC settings in advance, maintaining comfort while minimising energy use. Furthermore, occupancy-based adjustments allow the system to forecast when residents will be home and adjust heating or cooling systems accordingly, ensuring comfort without wasting energy when the house is unoccupied.

In terms of appliance usage optimisation, predictive maintenance utilises appliance usage patterns and performance data to predict potential failures or maintenance needs, enabling proactive maintenance and reducing downtime. Predictive models also recommend the most energy-efficient times to use certain appliances based on patterns of use and energy pricing. Security enhancements benefit from predictive analytics by identifying unusual behaviour patterns that might indicate security threats, such as unexpected entry attempts or unusual activity around the home. The system can provide proactive alerts, predict potential security breaches or safety issues, and automatically take preventive actions like locking doors or turning on lights [23].

Finally, predictive analytics contribute to a personalised user experience by anticipating residents' preferences for lighting, music, or temperature based on past behaviour, thus creating a more comfortable and tailored living environment. As the system collects more data over time, it continually improves its predictions, enhancing the user experience through adaptive learning.

4.2.3 Benefits of Predictive Analytics. Predictive analytics in smart homes offers numerous benefits, including enhanced efficiency, increased comfort, proactive maintenance, improved security, and a positive environmental impact. By optimising the performance of home systems, predictive analytics leads to significant energy and cost savings, ensuring that resources are utilised most efficiently through anticipating needs and proactive adjustments. This technology also enhances comfort by predicting residents' behaviours and preferences, allowing smart homes to adjust settings to match individual needs and maintain a consistently comfortable living environment. Proactive maintenance facilitated by predictive analytics minimises the likelihood of unexpected appliance failures, extending the lifespan of devices and ensuring their efficient operation. In terms of security, advanced predictive capabilities enable smarter security measures, offering early warnings and preventing potential security incidents. Additionally, the efficient use of energy resulting from predictive analytics reduces the carbon footprint of households, thus contributing to broader sustainability goals and environmental protection.

4.2.4 Challenges in Implementing Predictive Analytics. Implementing predictive analytics in smart homes faces several challenges, including data quality and quantity, privacy concerns, integration with existing systems, algorithm complexity, and user acceptance. Accurate predictive analytics depend on high-quality, comprehensive data; with complete and precise data, predictions can be correct, leading to suboptimal decisions. Privacy concerns arise from collecting and analysing detailed behavioural data, necessitating ethical and responsible data collection practices to maintain residents' trust. The complexity of integrating predictive analytics with existing smart home systems presents another challenge, as ensuring compatibility and seamless communication between devices is critical for effective implementation. Developing and maintaining sophisticated predictive models require machine learning and data science expertise, which can hinder widespread adoption due to the need for ongoing refinement and updating. Finally, user acceptance is crucial; residents must trust and feel comfortable using predictive analytics in their homes. Clear communication about the benefits and assurances regarding data privacy can help improve user acceptance and foster a positive perception of predictive analytics technologies.

4.3 Behavioural Interventions

Behavioural interventions in smart homes can significantly influence energy consumption patterns and promote sustainable practices. These interventions typically fall into four categories: feedback systems, automation, incentives, and nudges.

Feedback Systems provide residents with information about their energy usage, encouraging more efficient behaviours. Real-time feedback offers immediate data on energy consumption, helping residents understand the impact of their actions. Energy dashboards or smart meter displays show current electricity usage, alerting residents to high consumption periods and motivating them to reduce usage. Comparative feedback involves comparing a household's energy use with that of similar households, which can be displayed via apps or in-home displays. Such comparisons can motivate residents to adopt more efficient behaviours.

Automation streamlines energy-saving practices by pre-setting routines and making dynamic adjustments. Pre-set routines automate energy-saving behaviours based on learned patterns. For instance, lights can be programmed to turn off automatically when a room is unoccupied, or heating systems can lower the temperature during the night. Dynamic adjustments involve real-time changes based on sensor data, such as automatically cooling a room that becomes too warm or dimming lights when no one is in the room. These automated interventions reduce the need for manual adjustments and ensure continuous energy efficiency.

Incentives encourage residents to adopt sustainable behaviours through rewards and goal-setting. Reward programs offer tangible benefits for reduced energy consumption, such as discounts on utility bills, points redeemable for eco-friendly products, or community recognition. Goal setting involves encouraging residents to set and achieve energy-saving targets, with smart home systems tracking progress towards these goals and providing positive reinforcement, fostering a sense of accomplishment and promoting sustainable practices.

Nudges are subtle environmental prompts or changes that encourage sustainable behaviours without being intrusive. Environmental cues, such as placing reminders to turn off lights or using energy-efficient modes on appliances, nudge residents towards more sustainable actions. Default settings, such as lower heating temperatures or shorter washing machine cycles, provide a baseline of efficiency that can lead to significant energy savings. Residents can override these defaults if needed, but having energy-efficient settings as the default option encourages sustainable behaviour with minimal effort.

Implementation of Behavioural Interventions involves personalised recommendations, interactive interfaces, and community programmes. Personalised recommendations, such as custom alerts and suggestions, can be provided by smart home systems based on collected data. For example, if the system detects that lights are frequently left on in unoccupied rooms, it can send reminders to turn them off or suggest setting up automated lighting controls. Smart home apps and interfaces can also offer tailored energy-saving tips based on residents' usage patterns, helping them identify specific actions to reduce energy consumption.

Interactive interfaces play a crucial role in engaging residents with their energy usage. User-friendly dashboards display energy consumption data in an easily understandable format, enabling residents to track their usage and identify areas for improvement. These dashboards can be accessed via smartphones, tablets, or dedicated in-home displays. Moreover, mobile apps that gamify energy-saving efforts can enhance engagement by offering challenges, tracking progress, and rewarding residents for achieving energy-saving milestones.

Community programmes further support the implementation of behavioural interventions. Energy challenges at the community level can encourage collective action, with residents participating in competitions to see who can reduce their energy consumption the most, fostering a sense of community and shared responsibility. Peer support groups, whether within neighbourhoods or online platforms, enable residents to share tips and experiences related to energy conservation, creating a supportive environment for sustainable behaviour change.

Impact of Behavioural Interventions includes significant reductions in energy consumption, lower utility bills, enhanced comfort and convenience, and long-term behavioural change. Real-time feedback and automation make residents more aware of their usage and reduce waste, leading to lower energy usage and utility bills. Environmental benefits are substantial, as reduced energy consumption leads to a lower carbon footprint, contributing to broader environmental sustainability goals. Smart homes are crucial in mitigating climate change by promoting energy-efficient behaviours. Additionally, behavioural interventions can promote the conservation of other resources, such as water, by encouraging efficient usage and reducing waste.

Enhanced comfort and convenience are notable impacts of behavioural interventions. Automated systems that adjust lighting, heating, and cooling based on occupancy and preferences ensure a comfortable living environment. These interventions optimise settings in real time, enhancing the home's overall comfort. Furthermore, automation and personalised recommendations reduce the effort required from residents to manage their home systems, making it easier to adopt and maintain sustainable behaviours.

Long-term behavioural change is another significant impact of these interventions. Sustained exposure to feedback and automated systems helps residents develop long-term energy-saving habits. Over time, these habits can become ingrained, leading to lasting behavioural changes. Moreover, behavioural interventions raise awareness about energy consumption and its broader impact, influencing residents' behaviours beyond the home environment. This increased awareness fosters a culture of sustainability and conscientious resource use.

Behavioural interventions are critical in smart homes, leveraging data and predictive analytics to encourage sustainable and efficient behaviours among residents. Through feedback systems, automation, incentives, and nudges, these interventions can significantly reduce energy consumption, lower utility bills, and enhance overall quality of life. By making sustainable behaviours more accessible and rewarding, behavioural interventions in smart homes contribute to a more sustainable future, benefiting residents and the environment.

4.4 Adoption and User Engagement

Smart home technologies' successful adoption and user engagement are crucial for maximising their potential benefits regarding energy efficiency, convenience, security, and sustainability. However, several challenges and strategies are associated with encouraging widespread adoption and sustained engagement among users. This section explores the factors influencing adoption, barriers to user engagement, and practical approaches to enhance both.

Smart home technologies' adoption and user engagement are critical for realising their full potential regarding energy efficiency, convenience, security, and sustainability. Addressing factors that influence adoption, overcoming barriers to engagement, and implementing effective strategies are essential for promoting the widespread use of these technologies. Through education, financial incentives, user-friendly design, robust customer support, and strong privacy and security measures, smart home technologies can become integral to modern living, contributing to a more sustainable and efficient future.

4.4.1 Factors Influencing Adoption. Several factors, including perceived benefits, affordability, ease of use, and brand trust and reputation, influence the adoption of smart home technologies.

Perceived Benefits: The convenience of remotely controlling home systems and automating routine tasks is highly appealing to potential users. Features such as remote monitoring, voice control, and scheduled operations significantly enhance daily life convenience. Additionally, the promise of energy savings and lower utility

bills is a strong motivator for adoption, with technologies demonstrating clear energy-saving benefits that are particularly attractive. Enhanced security, provided through advanced features like real-time alerts, remote surveillance, and automated responses, also appeals to users concerned about home safety.

Affordability: The initial cost of purchasing and installing smart home devices can be a barrier to adoption. Therefore, systems and devices with lower initial costs or available financing options are generally more accessible to a broader audience. Furthermore, demonstrating long-term savings from reduced energy bills and maintenance costs can help justify the initial investment. Clear and tangible return on investment (ROI) figures are particularly persuasive for potential adopters.

Ease of Use: Smart home devices that are easy to set up and use, featuring intuitive interfaces and clear instructions, are more likely to be adopted. Conversely, complex or cumbersome systems can deter users. Compatibility with existing home systems and other smart devices also simplifies adoption, as seamless integration reduces the learning curve and enhances the overall user experience.

Brand Trust and Reputation: Technologies from reputable brands are more likely to be adopted by users. Well-established companies with a history of reliable products and good customer service have a competitive advantage in the market. Additionally, other users' word-of-mouth recommendations and positive online reviews significantly influence adoption decisions.

4.4.2 Barriers to User Engagement. Several barriers can hinder user engagement with smart home technologies, including privacy and security concerns, technological complexity, and a need for more awareness and understanding.

Privacy and Security Concerns: Concerns about data privacy, such as the collection, use, and sharing of personal information, can deter users from adopting smart home technologies. Addressing these concerns requires transparency and robust privacy policies. Additionally, the potential for cybersecurity risks, including hacking and unauthorised access to smart home systems, can cause anxiety among users. Ensuring strong security measures and regular updates is crucial for maintaining user trust and confidence.

Technological Complexity: The complexity of setup processes can frustrate users and lead to disengagement if the initial installation is too complicated and time-consuming. Simplifying setup procedures and providing comprehensive support can help mitigate this barrier. Furthermore, ongoing technical difficulties, such as connectivity problems or device malfunctions, can diminish user satisfaction and engagement. Ensuring reliable performance and responsive customer support are essential to maintaining user interest and satisfaction.

Lack of Awareness and Understanding: Many potential users may need help understanding the capabilities and benefits of smart home technologies, leading to a knowledge gap. Educational initiatives and clear communication can help bridge this gap and enhance user engagement. Additionally, addressing common misconceptions about smart home technologies, such as perceived high costs or complexity, is vital for encouraging adoption and demonstrating the practical benefits of these systems.

5 PRIVACY CONCERNS

Privacy concerns are significant regarding deploying and using smart home technologies, including behavioural modelling for sustainability. Collecting, storing, and analysing detailed personal data can pose risks to residents' privacy if not appropriately managed. Below, we explore various aspects of privacy concerns, including data collection practices, potential risks, regulatory frameworks, and strategies for mitigating these concerns. Privacy concerns are a critical consideration when deploying and using smart home technologies. The collection, storage, and analysis of detailed personal data can pose significant risks to residents' privacy if not appropriately managed. The privacy risks associated with smart home technologies can be mitigated by implementing robust security measures, ensuring user control and transparency, adhering to regulatory frameworks, and educating residents. Addressing these concerns is essential for building trust and encouraging the adoption of smart home systems, ultimately contributing to a more sustainable and efficient future.

5.1 Data Collection Practices

Smart home devices use extensive data collection practices, gathering information through continuous monitoring and integration with other devices. Users must often provide personal information, such as names, addresses, and contact details, during setup and registration. These devices also collect detailed behavioural data, tracking residents' occupancy patterns, daily routines, and preferences for heating, cooling, lighting, and appliance usage. Additionally, sensors within smart homes gather environmental data, including temperature, humidity, and air quality, which can indirectly reveal residents' activities.

Smart home devices operate continuously, collecting real-time data essential for their functionality. However, this constant data flow raises privacy concerns due to the volume and granularity of the information collected. Moreover, integrating multiple devices and platforms within smart home ecosystems leads to data aggregation from various sources. This comprehensive data collection results in detailed profiles of residents' behaviours and habits, enhancing the system's effectiveness and necessitating robust data privacy measures.

5.2 Potential Risks

Smart home devices pose several potential risks, including unauthorised access, data breaches, surveillance, and behavioural profiling. These devices are vulnerable to hacking and other cybersecurity threats, which can lead to unauthorised access and data breaches, exposing sensitive information about residents. The personal and behavioural data collected by smart home devices can be valuable to malicious actors, and theft of this data can result in identity theft, financial fraud, and other forms of exploitation.

Continuous monitoring by smart home devices can invade residents' privacy, as it involves constantly collecting data on their activities, potentially making them feel surveilled within their own homes. Furthermore, detailed data collection can create comprehensive profiles of residents' behaviours, preferences, and routines. These profiles can be used for targeted advertising, discrimination,

or other purposes without the residents' consent, raising significant ethical and privacy concerns.

5.3 Regulatory Frameworks

Various regulatory frameworks govern Smart home technologies to protect user data and ensure privacy. Data protection regulations such as the General Data Protection Regulation (GDPR) in the European Union and the California Consumer Privacy Act (CCPA) set strict data collection, processing, and storage guidelines. The GDPR mandates that users give explicit consent for their data to be collected and used, and it provides residents with rights to access, correct, and delete their data. Similarly, the CCPA grants California residents the right to know what personal data is being collected and to whom it is sold and the right to access and delete their data.

Industry standards and best practices also play a crucial role in safeguarding privacy. Privacy by Design involves integrating privacy measures into the design and development of smart home technologies, ensuring that privacy considerations are addressed proactively rather than as an afterthought. Additionally, data anonymisation, which involves removing personally identifiable information (PII) from datasets, helps protect residents' identities while allowing for aggregated data analysis. These regulatory frameworks and best practices collectively mitigate privacy risks and enhance the protection of user data in smart home environments.

Several mitigation strategies can be implemented to address the privacy and security concerns associated with smart home technologies. Enhanced security measures such as solid encryption for data in transit and at rest can protect sensitive information from unauthorised access, ensuring that intercepted data cannot be easily read or misused. Additionally, keeping smart home devices and systems updated with the latest security patches is crucial for protecting against known vulnerabilities and reducing the risk of cyberattacks.

User control and transparency are also vital components of effective mitigation strategies. Providing clear and user-friendly mechanisms for residents to give and withdraw consent for data collection and use ensures that individuals maintain control over their personal information. Furthermore, enabling data portability, which allows residents to transfer their data between service providers quickly, can enhance user control, foster trust, and encourage competition and innovation among providers.

Clear privacy policies and resident education are significant in building trust and ensuring transparency. Developing and communicating explicit privacy policies that detail what data is collected, how it is used, and with whom it is shared can help establish transparency. Educating residents about potential privacy risks and guiding protecting their data empowers them to make informed decisions, including setting up and managing privacy settings on their smart home devices.

Third-party audits and certifications further reinforce data protection efforts. Regular independent audits of smart home systems can ensure compliance with privacy regulations and industry standards, identifying potential vulnerabilities and areas for improvement. Additionally, obtaining privacy certifications from recognised organisations signals to residents that a smart home system adheres to high data protection and privacy standards. These combined strategies can significantly mitigate privacy and security risks in smart home environments.

6 CONCLUSIONS AND FUTURE RESEARCH DIRECTIONS

The integration of smart home technologies represents a significant advancement in promoting sustainability, enhancing convenience, and improving the quality of life for residents. By deploying interconnected devices and advanced data analytics, smart homes offer a proactive approach to managing energy consumption, reducing environmental impact, and fostering sustainable living practices.

Collecting and analysing detailed behavioural data enables smart homes to anticipate residents' needs and optimise energy use. Predictive analytics, driven by machine learning algorithms and data mining techniques, are crucial for identifying patterns and making informed adjustments to home systems. Effective behavioural interventions, such as real-time feedback, automation, incentives, and nudges, are essential for encouraging sustainable behaviours among residents. These strategies help raise awareness, motivate energy-saving actions, and facilitate the adoption of eco-friendly practices.

While case studies on smart technologies highlight their practical benefits, they also reveal opportunities for further research. Potential research directions include exploring more sophisticated machine learning models for predictive analytics, developing advanced algorithms for behavioural interventions, and investigating the long-term effects of gamification on sustainable practices. Research could also focus on optimising the integration of smart home technologies with renewable energy sources and enhancing the interoperability of devices to create more cohesive smart home ecosystems.

Addressing privacy concerns through robust security measures, transparent data policies, and user education is crucial for maintaining trust and ensuring the ethical use of collected data. Further research is needed to develop innovative privacy-preserving techniques and to understand the balance between data utility and privacy protection in smart homes.

Promoting the adoption and sustained engagement of smart home technologies requires a multifaceted approach. Future research could explore the most effective methods for educating users about the benefits of smart home technologies, strategies for reducing the initial costs of adoption, and ways to simplify the user experience. Investigating the impact of brand trust and user testimonials on adoption rates could provide valuable insights for market strategies.

As smart home technologies evolve, advancements in artificial intelligence, machine learning, and data analytics will significantly enhance their capabilities. These improvements will enable more precise behavioural modelling, energy optimisation, and personalised user experiences. Research can further explore how these advancements can be harnessed to create even more efficient and user-friendly smart homes.

Policy and regulation play a critical role in safeguarding user privacy and building trust in smart home technologies. Research into the effectiveness of current regulations and the development of new frameworks that keep pace with technological advancements

is essential. Policymakers must ensure these regulations address emerging privacy and security concerns to protect users effectively.

The smart home market is poised for significant growth, driven by increasing consumer awareness, technological innovation, and the rising demand for sustainable living solutions. Research into market trends, consumer behaviour, and the effectiveness of strategic partnerships between technology providers, utility companies, and government agencies will be crucial in driving further adoption and fostering innovation within the industry.

The widespread adoption of smart home technologies has the potential to make a substantial contribution to global sustainability efforts. Research into the environmental impact of smart homes, the optimisation of energy use, and the promotion of renewable energy sources will be essential in addressing the environmental challenges of the future.

Smart home technologies offer a transformative approach to achieving sustainability, enhancing convenience, and improving residents' overall quality of life. By leveraging advanced data analytics and behavioural modelling, these technologies can optimise energy consumption, reduce environmental impact, and foster eco-friendly practices. However, addressing privacy concerns and promoting user adoption and engagement is essential for realising the full potential of smart homes. As the industry evolves, smart home technologies will undoubtedly play a pivotal role in shaping a more sustainable and efficient future.

ACKNOWLEDGMENTS

This study was carried out within the ASSISTANTS project – funded by European Union – Next Generation EU within the PRIN 2022 PNRR program (D.D.1409 del 14/09/2022 Ministero dell'Università e della Ricerca). This manuscript reflects only the authors' views and opinions and the Ministry cannot be considered responsible for them.

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