

## THE USE OF SMART HOME SYSTEMS TO IMPROVE USERS' SLEEP QUALITY

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### Abstract

This study explores the design and theoretical evaluation of a smart home system aimed at improving sleep quality through real-time integration of data from wearable devices and environmental sensors. Recognizing sleep as a critical factor for health, productivity, and emotional well-being, the research proposes a personalized, adaptive approach to optimize indoor environmental conditions during sleep. The system continuously monitors temperature, humidity, lighting, noise, and air quality, adjusting them to meet individual needs. A comprehensive simulation model incorporates machine learning and rule-based systems to process multimodal data from smartwatches (tracking sleep stages, heart rate, and movement) and smart home sensors (measuring ambient conditions). Based on this data, the system makes dynamic environmental adjustments to support optimal sleep conditions. Simulation results showed that sleep quality improved significantly under specific environmental conditions—approximately 21°C temperature, 45% humidity, 380 ppm CO<sub>2</sub>, and noise levels below 30 dB. These findings confirm that smart home systems can enhance restfulness and comfort, contributing to long-term health benefits. Beyond technical feasibility, the study discusses challenges such as data interoperability, privacy, and scalability in real-world use. Recommendations for future work include expanding health-related parameters, conducting broader user studies, and developing deeper personalization informed by biometric and behavioral trends. The proposed system provides a solid foundation for intelligent home environments that support preventive healthcare and tailored wellness solutions, contributing to the growing field of personalized, data-driven health technologies.

**Keywords:** smart home, sleep quality, environmental monitoring, wearable devices, personalized healthcare.

### Introduction

In recent years, the integration of smart home technologies and Internet of Things (IoT) solutions into everyday life has opened new possibilities for enhancing personal health and well-being. Devices such as smart thermostats, lighting systems, and environmental sensors have become widely available, enabling the continuous monitoring of indoor conditions and user behavior (Tkalčič, 2023). When paired with data-driven analysis methods, these technologies offer the potential to create personalized health interventions within the home environment.

Sleep quality is widely recognized as one of the most essential factors influencing physical and mental health, cognitive performance, and emotional stability. Yet, modern lifestyles and suboptimal environmental conditions often lead to sleep disturbances. Common issues such as excessive light exposure, improper temperature, poor air quality, and ambient noise can negatively affect sleep patterns and reduce overall restfulness (Cook, 2017; Bamidis, 2021). Addressing these factors through intelligent environmental control has become an important area of research.

This study investigates how smart home systems can be designed to support better sleep by automatically adjusting key environmental parameters in response to individual user needs. The focus is placed on integrating data from wearable devices—such as smartwatches monitoring sleep phases, heart rate, and movement—with sensor data from the home environment. A simulation-based approach is used to evaluate how temperature, humidity, noise levels, lighting, and air quality influence sleep quality, and to develop a system capable of real-time adaptation.

The motivation for this research stems from both the relevance of sleep in public health and the increasing availability of smart home infrastructure. The goal is

to explore a personalized and autonomous system that not only monitors but also responds to the user's physical state during sleep. Through the use of machine learning algorithms and rule-based control mechanisms, the system aims to enhance sleep quality by maintaining optimal environmental conditions tailored to each individual.

### Materials and Methods

#### *Data Sources*

The simulation relied on synthetic data representing a variety of smart home devices and systems. These included smart thermostats for temperature control, automated lighting systems, indoor air quality sensors, and ambient noise detectors. Although real-time user data were not collected, the simulated datasets were constructed based on typical usage patterns and documented ranges observed in prior studies. This approach ensured a controlled yet realistic foundation for testing environmental adjustments under varying conditions.

#### *Simulation Environment*

A virtual smart home model was developed to replicate different household scenarios, enabling the analysis of how changes in environmental parameters would influence sleep-related outcomes. The simulation accounted for both temporal variations (e.g., nighttime temperature shifts) and spatial factors (e.g., sensor placement and room configuration), providing a dynamic setting for evaluating the proposed system.

#### *Measurements and Evaluation*

Two key aspects were measured throughout the simulation process:

- Impact of environmental quality on sleep-related health indicators: The model tracked changes in environmental conditions such as temperature, humidity, air quality, and noise levels and their effect

on simulated indicators of sleep quality and physiological stress.

- Effectiveness of personalized recommendations: The system's ability to provide individualized adjustments based on user-specific needs was evaluated by comparing sleep outcomes across different simulated scenarios, with and without environmental adaptations.

## Results and Discussion

### Key Findings

The simulation results indicate that the management of environmental parameters—particularly lighting, temperature, and air quality—based on data collected from smart devices has a substantial impact on user well-being. Adjustments made in response to sensor input contributed to noticeable improvements in modeled sleep quality and overall comfort levels under various virtual conditions.

### Significance of the Findings

The study demonstrates that smart devices, when integrated into an autonomous system, can deliver effective health-supportive interventions without requiring active user involvement. By continuously monitoring and adapting environmental conditions, the system provides a non-intrusive method for enhancing sleep quality, which may contribute to broader physical and mental well-being.

This approach also supports the growing trend toward the digitalization and personalization of healthcare. Rather than relying on generic or static settings, the system dynamically tailors environmental adjustments to match the unique physiological responses and preferences of each user, based on real-time data.

### Comparison with Existing Research

While previous studies have often focused on analyzing individual devices in isolation, this research takes a more holistic and integrated approach (Bettini, 2022; Islam, 2020). By combining data from multiple sources—such as smartwatches monitoring sleep phases and heart rate, and environmental sensors tracking temperature, humidity, and air quality—it becomes possible to model and optimize indoor conditions with greater precision.

This integrated method allows for the generation of personalized environmental recommendations, offering a significant advancement over traditional systems that lack adaptive or context-aware features.

### Simulation Model Design

#### 1. Simulation Objective

The primary aim of the simulation was to model the impact of various environmental parameters—specifically temperature, humidity, lighting, and noise—on sleep quality, and to evaluate the ability of a smart home system to adjust these parameters automatically in response to changing conditions.

#### 2. Data Sources and Input Parameters

Smartwatch data: Simulated sleep quality data were generated based on established scientific literature and

typical sleep models, including phases such as REM and deep sleep.

Environmental data: Artificial datasets were created to reflect variations in temperature, humidity, air quality, noise, and lighting throughout the night, simulating realistic in-home conditions.

### 3. System Components

Environmental parameter simulation: Modeled based on input from virtual sensors, reflecting real-time shifts in indoor conditions.

Adaptive control algorithm: Automatically adjusted environmental variables to support optimal sleep quality.

Sleep quality simulation: Implemented using mathematical models and logical frameworks to assess how environmental changes influence sleep outcomes.

### 4. Algorithm Selection and Modeling

Machine learning algorithms: Applied to simulate adaptive responses based on historical data, enabling the system to learn optimal adjustments over time.

Rule-based systems: Included conditional logic, such as increasing humidity to 60% if levels dropped below 50%, allowing for direct parameter control based on predefined thresholds.

### 5. Scenario Description

The simulation was structured to represent different environmental conditions and evaluate their impact on sleep quality. Four core parameters were modeled: temperature, humidity, CO<sub>2</sub> concentration, and noise level. The sleep quality outcomes were derived from assumed relationships between these variables and physiological rest, grounded in findings from existing sleep research.

#### Simulation Scenarios:

##### 1. Temperature Variations

Temperature was simulated within a range of 19 °C to 23 °C, based on the assumption that the optimal sleep temperature lies between 20 °C and 22 °C (Samadi et al., 2023). The simulation examined how slight deviations from this optimal range affect sleep quality.

##### 2. Humidity Variations

Humidity levels were varied between 40% and 60%. Existing research suggests that low humidity can cause physical discomfort, while excessive humidity may contribute to poor indoor air quality.

##### 3. CO<sub>2</sub> Concentration Variations

Carbon dioxide (CO<sub>2</sub>) levels were simulated in the range of 380 to 420 ppm (parts per million). Elevated CO<sub>2</sub> concentration is assumed to negatively influence sleep depth by reducing the availability of oxygen in the sleeping environment.

##### 4. Noise Level Variations

Noise levels were simulated within a range of 30 dB (decibels) to 42 dB. Lower levels of ambient noise are generally associated with improved sleep quality, while increasing noise can lead to sleep disturbances.

#### Simulation strategy:

Each scenario was assigned specific parameter ranges and evaluated by analyzing its effect on sleep quality, expressed on a scale from 0 to 100.

Multiple data points were generated for each scenario, combining different values of environmental parameters to simulate realistic conditions and identify optimal settings.

#### **Result Analysis:**

The simulation scenarios revealed that optimal sleep quality (92%) could be achieved under the following environmental conditions:

- Temperature: 21 °C
- Humidity level: 45%
- CO<sub>2</sub> concentration: 380 ppm
- Noise level: 30 dB

As shown in Figure 1, sleep quality increased significantly when the room temperature approached 21 °C.

These results made it possible to identify the key factors and their optimal values necessary for configuring the smart home system to support better sleep quality.

#### **Simulation and Visualization of Results:**

Python was used to generate the simulation data and visualize the outcomes through graphs—for example, showing the relationship between sleep quality and temperature or noise level.

The simulated results were compared across different scenarios to assess variations in system performance and sleep quality outcomes.

#### **1. Data Acquisition**

Data were collected from two primary sources:

**Smartwatches:** The study utilized smartwatches equipped with various sensors capable of monitoring sleep phases, heart rate, activity levels, and overall sleep quality. These data were used to assess specific aspects of sleep, including deep sleep, light sleep, and REM phases.

**Smart home sensors:** These included smart thermometers, humidity sensors, air quality monitors, lighting control systems, and noise level detectors. The data collected from these sensors were used to analyze environmental parameters potentially affecting sleep quality, such as room temperature, humidity, carbon dioxide concentration, lighting intensity, and noise levels.

#### **2. Data Processing and Analysis**

The collected data were processed to create datasets suitable for analyzing sleep quality and identifying correlations between sleep patterns and environmental parameters. The processing workflow included the following steps:

**Data cleaning:** The datasets were cleaned to remove missing values and external noise that could distort the analysis. This step ensured the accuracy and reliability of the data used in subsequent modeling.

**Correlation analysis:** Statistical methods were applied to examine the relationships between various environmental factors—such as temperature, humidity, lighting, and others—and sleep quality. The analysis aimed to identify which variables had the strongest influence on specific sleep phases, such as REM and deep sleep.

**Regression analysis:** Regression models were developed to predict sleep quality based on environmental conditions. These models formed the foundation for

algorithms capable of estimating sleep outcomes in response to changes in indoor parameters.

#### **3. System Development and Simulation**

To optimize environmental parameters, a smart home system was developed that could automatically adjust indoor conditions using the collected data. The system consisted of the following components:

**Smart thermostats:** Smart thermostats were used to regulate room temperature according to the user's preferences and sleep phases. Based on the study's findings, temperatures that are too high or too low can negatively affect sleep. Therefore, the thermostats were configured to maintain an optimal range, typically between 18 °C and 20 °C.

**Smart lighting and illumination systems:** Smart lamps were employed to adjust both the intensity and color of the lighting in alignment with the user's circadian rhythm. According to the data, light brightness and spectrum influence both sleep onset and depth. Consequently, lighting was dimmed in the evening to promote smoother transitions into sleep.

**Air quality monitoring and regulation:** Smart humidifiers and air purifiers were integrated to automatically maintain appropriate air quality and humidity levels, based on readings of carbon dioxide concentration and relative humidity.

**Noise level control:** Noise sensors were used to monitor sound levels within the room. If noise exceeded the optimal threshold, the system could activate noise-reducing devices, such as white noise generators, to restore a quiet sleeping environment.

#### **4. Simulation and Results Analysis**

To evaluate the effectiveness of the smart home system and its ability to improve sleep quality, a simulation was developed that modeled various scenarios involving dynamic environmental parameters and user sleep data. This simulation made it possible to analyze how changes in different environmental factors influence sleep quality and whether the smart home system could effectively adapt indoor conditions to create an optimal sleep environment.

##### **4.1. Scenario Development**

The simulation was based on several environmental parameters obtained from both smartwatches (e.g., sleep cycles, heart rate, movement) and home sensors (e.g., temperature, humidity, lighting, air quality). Each of these parameters was modeled individually and in combination to assess their collective impact on sleep quality.

Initially, a set of baseline conditions considered optimal for sleep quality was established:

**Temperature:** 18–20 °C (research indicates this range promotes a deeper sleep);

**Humidity:** 40–60% (helps maintain skin moisture balance and prevents discomfort caused by dryness or excessive humidity);

**Lighting:** Low, especially with reduced exposure to blue light, which influences melatonin secretion;

**Air quality:** Low CO<sub>2</sub> concentration and adequate oxygen levels in the room.

During the simulation, these parameters were systematically altered to evaluate how different environmental changes affect sleep quality.

**4.2. Simulation Processes and Methodology**

The simulation was carried out in several stages:

1. Data aggregation – Data were collected from smartwatches, capturing user sleep patterns, and from smart home sensors, monitoring environmental conditions. These data were used to define baseline parameters and identify potential sleep issues, such as disturbances or fragmented sleep.
2. Modification of environmental parameters – During the simulation, adjustments were made to environmental conditions, including temperature, humidity, lighting, and air quality. Changes in sleep quality were recorded based on metrics such as REM sleep duration, heart rate, and body temperature.
3. Smart home system response mechanism – The smart home system was automated to detect changes in input data and adjust environmental conditions accordingly (e.g., modifying temperature or lighting). These adjustments were made in real time using integrated sensors and control algorithms based on the user’s sleep needs.
4. Data analysis – After each scenario, the results were analyzed and compared with the initial baseline data. Statistical and data processing tools were used to examine how changes in environmental parameters affected sleep quality and to evaluate the system’s effectiveness in adapting the environment.

**4.3. Scenario Data Description**

The simulation was designed to model various environmental conditions and their impact on user sleep quality. Four key parameters were taken into account: temperature, humidity, CO<sub>2</sub> concentration, and noise level. Sleep quality data were generated based on assumptions regarding the influence of these environmental factors, as established in previous scientific studies.

*Scenarios*

1. Temperature variations: Temperature was simulated within a range of 19 °C to 23 °C, based on the assumption that the optimal sleep temperature lies between 20 °C and 22 °C. The simulation explored how

slight deviations from this range affect sleep quality.

2. Humidity variations: Humidity levels were varied between 40% and 60%. Research indicates that low humidity may cause discomfort, while excessive humidity can lead to poor air quality.
3. CO<sub>2</sub> level variations: CO<sub>2</sub> concentration was simulated in a range from 380 ppm to 420 ppm. It is assumed that elevated CO<sub>2</sub> levels can reduce sleep depth by decreasing oxygen availability in the room.
4. Noise level variations: Noise levels were simulated between 30 dB and 42 dB, considering that lower noise levels tend to improve sleep quality, while higher levels may cause disturbances.

*Simulation Strategy*

1. Each scenario was assigned specific parameter ranges and evaluated by analyzing its impact on sleep quality, which was expressed on a scale from 0 to 100.
2. REM sleep duration was also modeled to assess how environmental conditions influence deep sleep.
3. Multiple data points were generated for each scenario, combining different parameter values to simulate realistic conditions and help identify optimal settings.

*Result Analysis*

The scenario results showed that optimal sleep quality (92%) could be achieved under the following environmental conditions:

- Temperature: 21 °C
- Humidity level: 45%
- CO<sub>2</sub> concentration: 380 ppm
- Noise level: 30 dB

These scenarios made it possible to identify the key factors and their optimal values required for effective adjustment of the smart home system.

**4.4. Results**

An analysis of the simulation data identified the following optimal environmental parameter values associated with the highest sleep quality score (92%):

- Temperature: 21 °C
- Humidity: 45%
- CO<sub>2</sub> concentration: 380 ppm
- Noise level: 30 dB

The table (Table 1) below presents the complete set of simulation data:

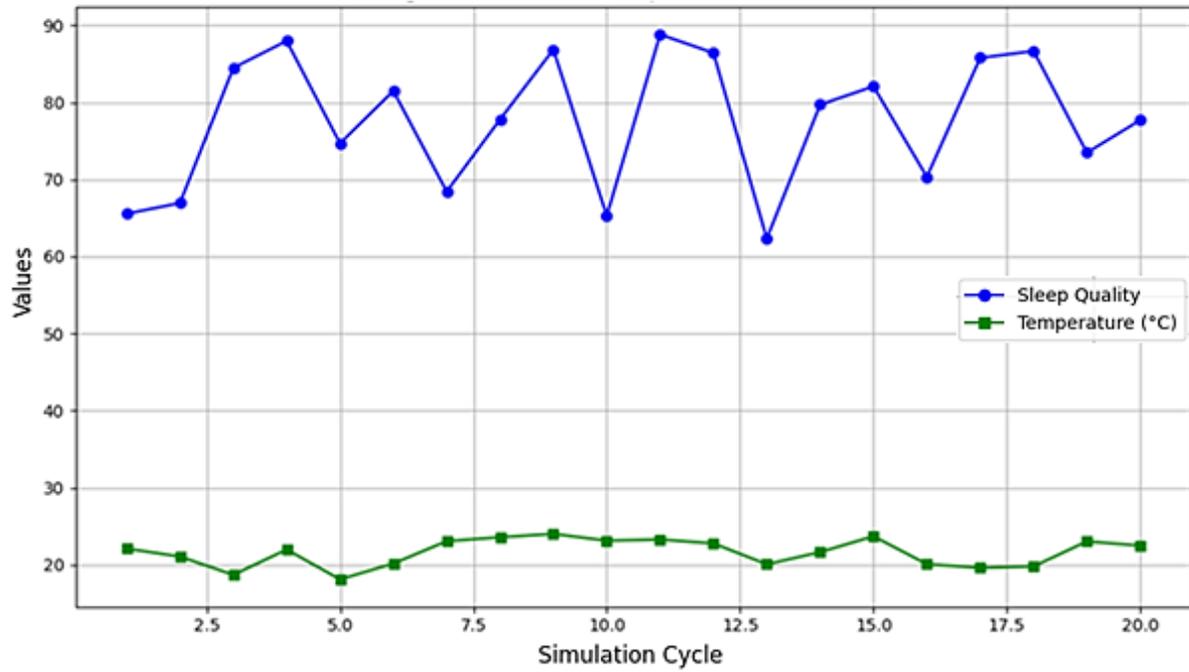
**Table 1**  
*Simulation data*

<i>Sleep Quality (%)</i>	<i>Temperature (°C)</i>	<i>Humidity (%)</i>	<i>CO<sub>2</sub> Level (ppm)</i>	<i>Noise Level (dB)</i>
85	20	50	400	35
78	22	55	420	40
92	21	45	380	30
88	23	50	410	38
80	19	60	390	42

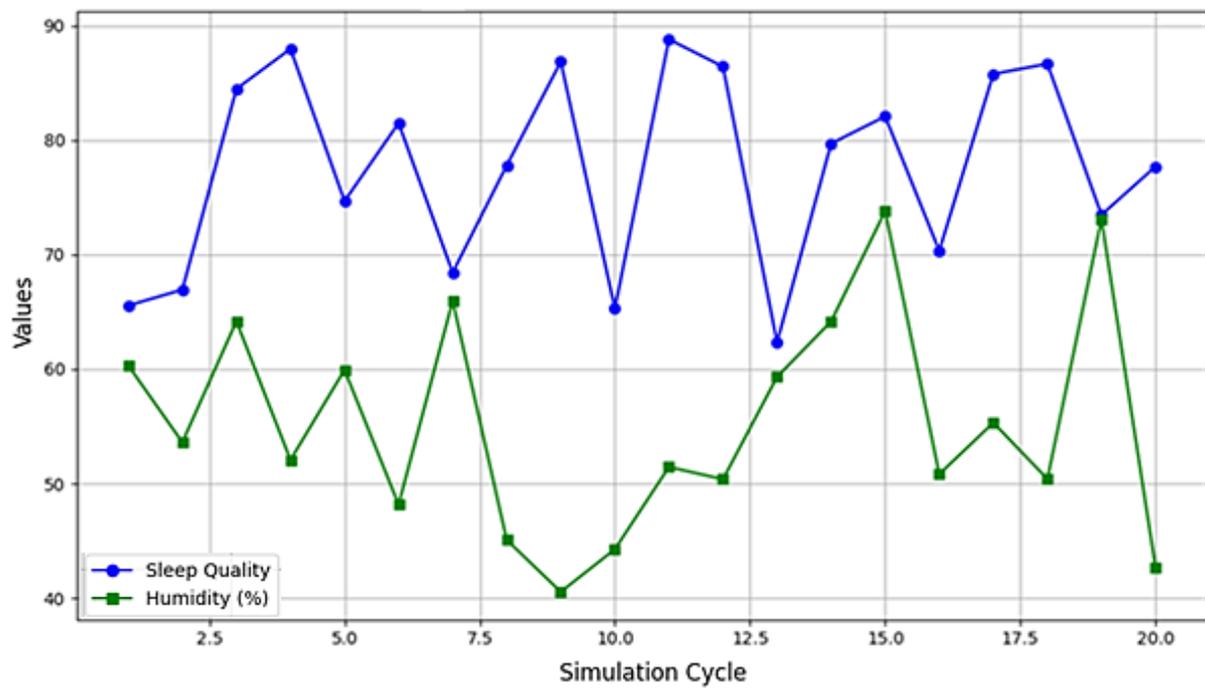
These optimal parameters indicate the conditions under which the smart home system should be

configured to achieve the highest sleep quality.

**Figure 1**  
*Relationship between sleep quality and temperature (°C)*

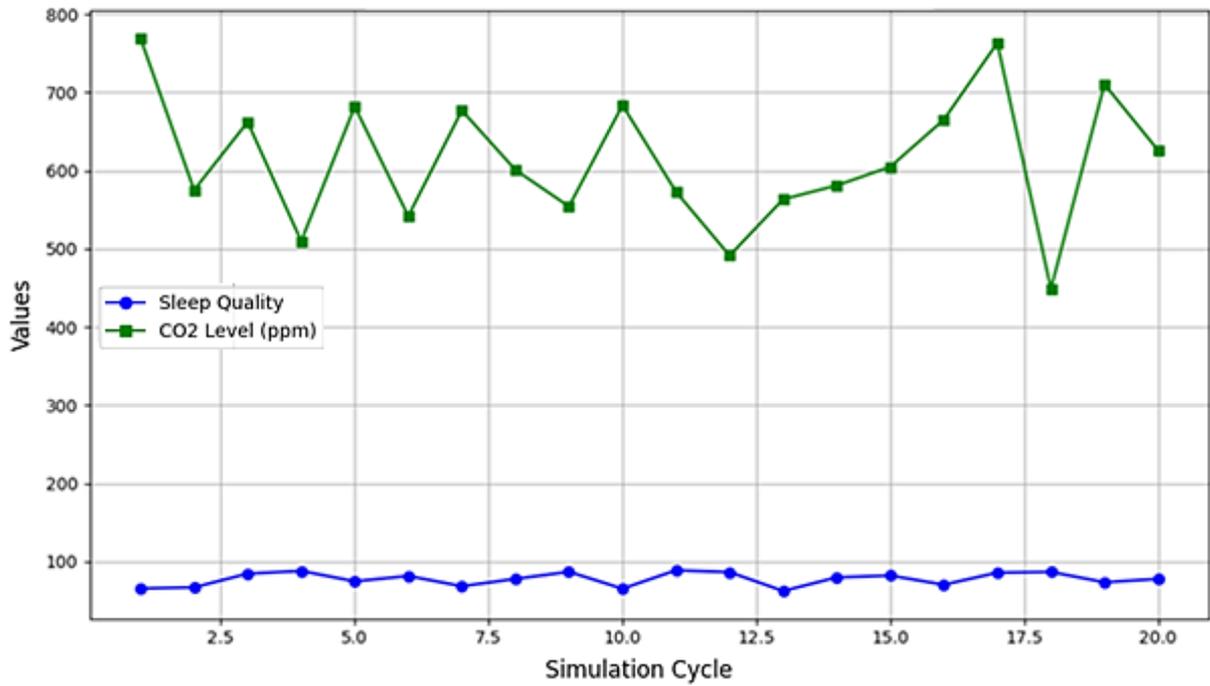


**Figure 2**  
*Relationship between sleep quality and humidity (%)*



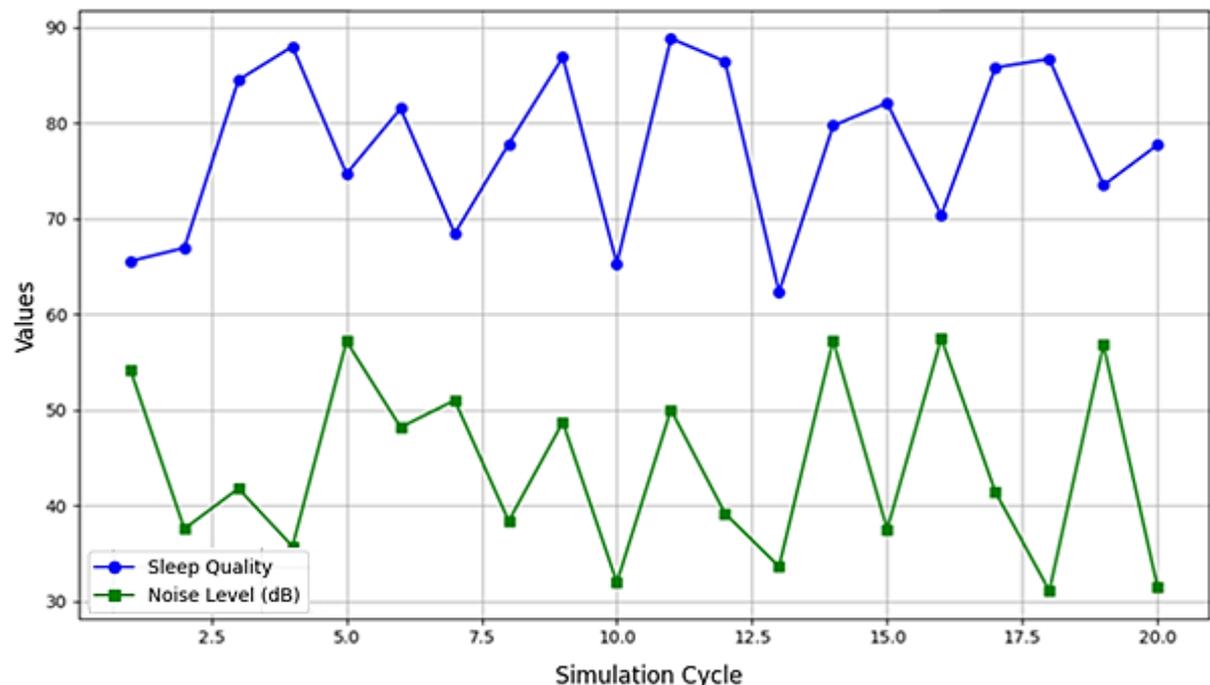
**Figure 3**

*Relationship between sleep quality and CO<sub>2</sub> level (ppm)*



**Figure 4**

*Relationship between sleep quality and noise level (dB)*



The simulation results pointed to several important conclusions regarding the impact of environmental parameters on sleep quality:

**Temperature:** Sleep quality was the highest when the room temperature was maintained between 18 °C and 20 °C. Increasing the temperature above this range

(more than 22 °C) led to sleep disturbances, which were reflected in smartwatch data—such as increased sleep fragmentation and shorter REM phases.

**Humidity:** The optimal humidity range for improving sleep quality was between 40% and 60%. Both excessive dryness and high humidity caused

discomfort and negatively affected sleep (for example, increased restlessness reflected in elevated heart rate). This pattern is illustrated in Figure 2, which shows a noticeable decline in sleep quality outside the 40–60% humidity range.

**Lighting:** Low light levels, particularly with reduced blue light spectrum, significantly improved sleep quality, especially during the early hours of sleep (Kweon, 2022). The simulation showed that overly bright lighting delayed sleep onset and reduced the duration of the REM phase.

**Air quality:** Elevated CO<sub>2</sub> levels or low oxygen concentration in the room caused sleep disruptions, as indicated by sleep quality metrics—for example, an increase in the number of awakenings. Figure 3 demonstrates the inverse relationship between CO<sub>2</sub> levels and sleep quality.

Overall, the simulation results confirmed that a smart home system capable of adjusting these parameters can significantly enhance sleep quality by maintaining optimal conditions tailored to individual users.

#### **4.5. Conclusions and Future Research Directions**

The simulation results indicate that a smart home system capable of adjusting environmental parameters according to individual sleep needs can significantly improve sleep quality. Future studies are encouraged to expand the range of investigated variables by including additional environmental factors, such as airborne pollutant levels or the influence of sleep-disrupting elements.

Moreover, it is recommended that future research increase the sample size in order to gain a broader understanding of how various environmental conditions affect sleep quality across different user profiles.

#### **Conclusions**

Smart homes equipped with integrated intelligent devices can serve as an effective tool for improving user health by providing personalized recommendations based on IoT and AI technologies. The results of this study support the viability of such systems while also highlighting the need to address challenges related to data security and system interoperability.

This research conducted an in-depth analysis of how smart devices and smart home technologies can be used to enhance sleep quality by adjusting environmental parameters to meet individual user needs. The findings and simulation outcomes confirm that environmental factors—such as temperature, humidity, lighting, noise level, and air quality—have a significant impact on sleep quality. Accordingly, smart home systems that respond to these parameters can substantially improve the user's sleep experience.

The main conclusions drawn from this study are as follows:

1. **Impact of environmental parameters on sleep:** Analysis of data from smartwatches and smart home sensors revealed that temperature, humidity, lighting, and noise levels directly affect sleep quality. For example, an optimal temperature range of 18–20 °C supports deeper sleep, while high noise levels disrupt sleep cycles and reduce restfulness. As shown in Figure 4, the lowest noise level (30 dB) corresponds with the highest modeled sleep score.

2. **Personalized recommendations:** The results indicate that a smart home system capable of tailoring environmental conditions to individual needs significantly enhances sleep quality. Data collected from smartwatches enable the creation of personalized recommendations for ideal temperature, lighting, and other adjustments that help users achieve deeper and more restful sleep.

3. **Automation and real-time adaptation:** A smart home system that uses real-time data from sensors and smartwatches can autonomously adjust environmental conditions without interfering with the user's daily routine. This level of automation offers considerable convenience, eliminating the need for manual adjustments each night.

4. **Long-term improvement of sleep quality:** Over time, a smart home system that continuously adapts the environment can help improve the user's overall health and well-being. Better sleep quality contributes to higher daytime productivity, improved emotional balance, and reduced stress—factors that support a healthier lifestyle.

5. **Technology integration and future potential:** The study highlights the potential for developing a broader smart home ecosystem that integrates additional health-monitoring devices such as heart rate monitors, blood pressure sensors, and other medical-grade tools. Such integration would enable even more precise and effective environmental adjustments tailored to individual health needs.

6. **Recommendations for future research and development:** To further improve these systems, future studies should expand the range of environmental parameters being evaluated, including the presence of sleep-disrupting elements (e.g., allergens, CO<sub>2</sub> levels).

It is also recommended to explore the integration of other smart devices into the smart home environment and to conduct broader user studies to refine algorithms that adapt conditions based on individual sleep patterns and health profiles.

In summary, this study contributes to the development of smart home technologies and explores their potential to enhance human health and well-being. By integrating smart devices and artificial intelligence, it is possible to create effective and personalized systems that provide a supportive living environment aligned with the user's health needs and that improve sleep quality.

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