

Design and development of an IoT-enabled smart pill box prototype with a smartphone app-based medication reminder

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Received 18 May 2025
Revised 8 January 2026
Accepted 23 January 2026

Abstract

Non-adherence to medication regimens remains a significant concern in healthcare, negatively impacting patient outcomes and increasing costs. This pilot study investigated using Internet of Things (IoT) and microcontroller technologies to enhance adherence through a smartphone-app-driven smart pill box. The prototype integrated an IoT-enabled microcontroller with a custom app designed to send real-time medication reminders and log pill box usage. Ten participants with chronic conditions requiring daily medication evaluated the device over four weeks. Adherence rates, self-reported before the trial, were compared to those monitored during the trial. Results indicated a marked improvement in adherence, increasing from 78% at baseline to 92% during the study. Additionally, 90% of participants rated the system as user-friendly and expressed willingness to continue its use. The study highlights the potential of this IoT-enabled smart pill box to address medication non-adherence effectively. However, further research with larger sample sizes is necessary to confirm its broader applicability across diverse populations and medical conditions. These findings suggest that integrating IoT and microcontroller technologies into adherence interventions could significantly benefit chronic disease management and healthcare outcomes. This innovative approach holds promise for addressing the widespread challenge of medication non-adherence, but larger and more demographically diverse studies are needed to validate its long-term effectiveness and generalizability.

Keywords: Internet of things, Medication adherence, Microcontroller, Smartphone app, Smart pill box

1. Introduction

Non-adherence to prescribed medication regimens remains a significant issue within the healthcare sector, affecting both individual patient outcomes and the broader healthcare system [1]. This problem leads to adverse health consequences such as increased complications and diminished quality of life, while imposing substantial financial burdens on healthcare systems worldwide [2-4]. Over the past decade, digital health technologies have emerged as promising tools to address this challenge. For instance, text message reminders can improve adherence rates by up to 19% according to Jeminiwa et al. [5]. Despite these advancements, many digital solutions remain limited to passive notification systems, lacking real-time monitoring and behavioral feedback. Studies indicate that systems capable of analyzing adherence patterns can enable timely and effective interventions when patients deviate from their prescribed regimens [6-8].

However, a critical gap persists regarding the integration of Internet of Things (IoT) and microcontroller technologies to develop proactive systems that not only remind patients but also monitor real-time medication-taking behavior [9-11]. Microcontrollers function as the central processors in smart pill boxes, coordinating hardware operations such as compartment activation, pill dispensation tracking, and reminder management [12, 13]. When integrated with IoT technology, these devices gain internet connectivity that enables seamless data exchange with a paired smartphone app [14, 15], facilitating real-time reminders, remote monitoring, and timely healthcare interventions [16-19]. Recent work has also demonstrated the potential of IoT-based medication management systems [20, 21]. By combining microcontroller precision with IoT's dynamic capabilities, the traditional pill box evolves into a sophisticated health management tool that offers real-time interaction and supports data-driven adherence tracking.

This study investigates the integration of IoT and microcontroller systems in designing and developing a smartphone-driven smart pill box to enhance medication adherence. The prototype actively interacts with users through timely reminders and adherence monitoring. The central objective of this research is to address the question: "How can IoT and microcontroller technologies be effectively designed and integrated within a smart pill box to support medication adherence among patients?" Unlike prior work, this study contributes by presenting a fully integrated IoT-microcontroller prototype with synchronized smartphone functionality, evaluated through real-world pilot testing of adherence outcomes.

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<https://doi.org/10.64960/easr.2026.262198>

2. Materials and methods

2.1 Design and development of a smart pill box prototype

A smart pill box was designed and developed through collaboration among software developers, engineers, and healthcare professionals. The prototype utilized an IoT-enabled microcontroller (ESP32) with integrated Wi-Fi to enable seamless communication between the device and a dedicated smartphone application. This integration facilitated real-time synchronization, allowing timely reminder alerts and data transmission regarding pill box usage [22, 23].

The prototype featured a lid-open sensor (infrared optical switch) to detect compartment access, RGB LEDs for visual cues, and a piezoelectric buzzer for auditory alerts. Power was supplied by a 5V rechargeable lithium battery. The smartphone app, developed in Android Studio (Java) for Android OS, communicated with the ESP32 microcontroller using the MQTT protocol. The app's main functions included schedule input, real-time reminders, a medication logbook with timestamps, and error notifications in case of synchronization failure. Future enhancements will include iOS compatibility and cloud-based data backup.

During bench testing, minor hardware issues such as LED malfunction, brief Wi-Fi reconnection delays, and one instance of app syncing difficulty were observed. These issues will be optimized in future iterations through enhanced component integration and firmware refinement to improve system stability. The conceptual framework of the pill box, covering its block diagram and circuit layout, is detailed in Figure 1.

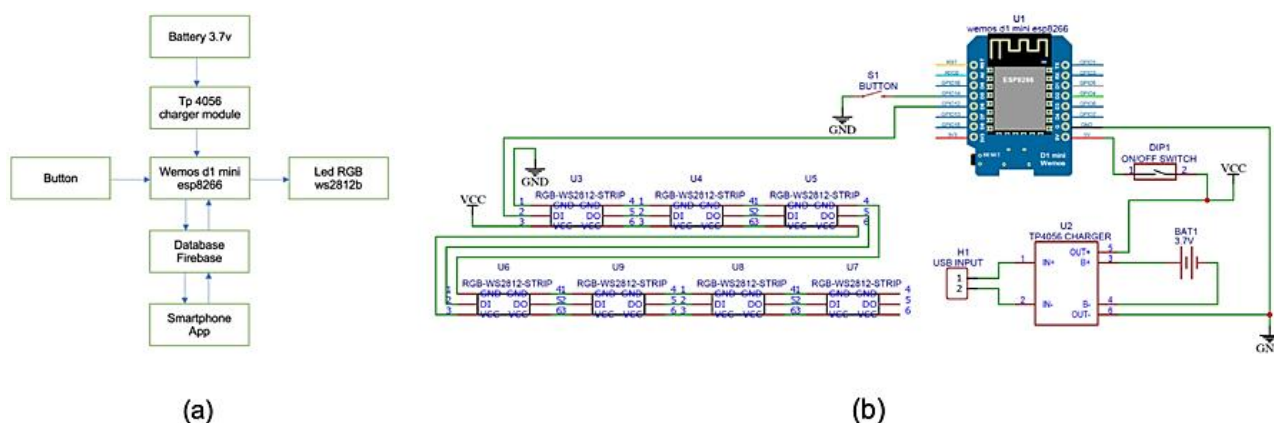


Figure 1 The concept of small pill box block diagram: (a) a flowchart illustrating the logic or process flow of the system and (b) an electrical schematic diagram detailing the connections between electronic components

2.2 Study design and participants

This study employed a pilot design to evaluate the functionality and effectiveness of the IoT-integrated pill box. The device utilized visual and auditory cues (LED lights and a buzzer) to remind participants at scheduled medication times, synchronized with the smartphone app. Participant recruitment followed purposive sampling with inclusion criteria: adults aged 18–65 years, diagnosed with a chronic condition requiring daily medication, and owning a smartphone. Exclusion criteria included hearing or visual impairments or inability to interact with the technology, ensuring feasibility and usability of the intervention.

2.3 Research instruments

The main instrument was the IoT-enabled smart pill box paired with a custom smartphone app. This design facilitated real-time communication, allowing users to manage schedules and receive reminders via their smartphones. A structured feedback form assessed: (1) self-reported adherence before and after device use; (2) user-friendliness; and (3) willingness for long-term adoption. A cohort of 10 participants with chronic conditions requiring daily medication participated in the four-week trial. Before the intervention, participants recorded adherence manually using a logbook. During the trial, adherence was automatically logged by the smart pill box and transmitted to the app in real time, allowing direct comparison between self-reported and recorded adherence rates.

2.4 Data analysis

A quantitative analysis was conducted to determine the device's impact on adherence. Adherence rates were calculated as the ratio of doses taken according to the prescribed schedule to the total prescribed doses, expressed as a percentage. A paired t-test compared pre-trial (self-reported) and post-trial (device-monitored) adherence rates. A Shapiro-Wilk test confirmed data normality, validating the use of parametric analysis. User feedback was analyzed descriptively through responses collected via Google Forms.

3. Results and discussion

3.1 Smart pill box prototype

In the development phase, a prototype of a smart pill box was comprehensively designed, leveraging the robust capabilities of IoT technologies alongside advanced microcontroller systems. The cornerstone of this design was an IoT-enabled microcontroller, seamlessly integrated with a custom-developed app to enable synchronized communication between the two platforms. It facilitated the instantaneous transmission of real-time medication reminders to users, enhancing adherence to prescribed regimens. Moreover, the pill box was equipped with a sophisticated mechanism to log the timing of user interactions with the device, ensuring that this

information was promptly transmitted to the app for both tracking and analysis. The prototype involved several innovative features aimed at optimizing both functionality and user experience. One of the standout features was a dual notification system. While the app was configured to issue timely reminders, the pill box itself was outfitted with an audible alarm and LED indicators that served as the visual alerts. This notification system was comprehensively designed to provide diverse user preferences, thereby enhancing usability and encouraging consistent engagement with the device. Technically, the operation of the pill box depends on the use of the app, where users input their medication schedules. The application communicates these schedules to the pill box via an internet connection, enabling the IoT-enabled microcontroller to activate the integrated alert mechanisms at the designated times. Figure 2 illustrates the pill box alongside the user interface of the smartphone app, showing the interplay between the hardware and software components.

Minor hardware inconsistencies identified during testing have been acknowledged, with planned refinements in future iterations. Subsequent phases will focus on firmware optimization and circuit improvements to further enhance operational reliability.

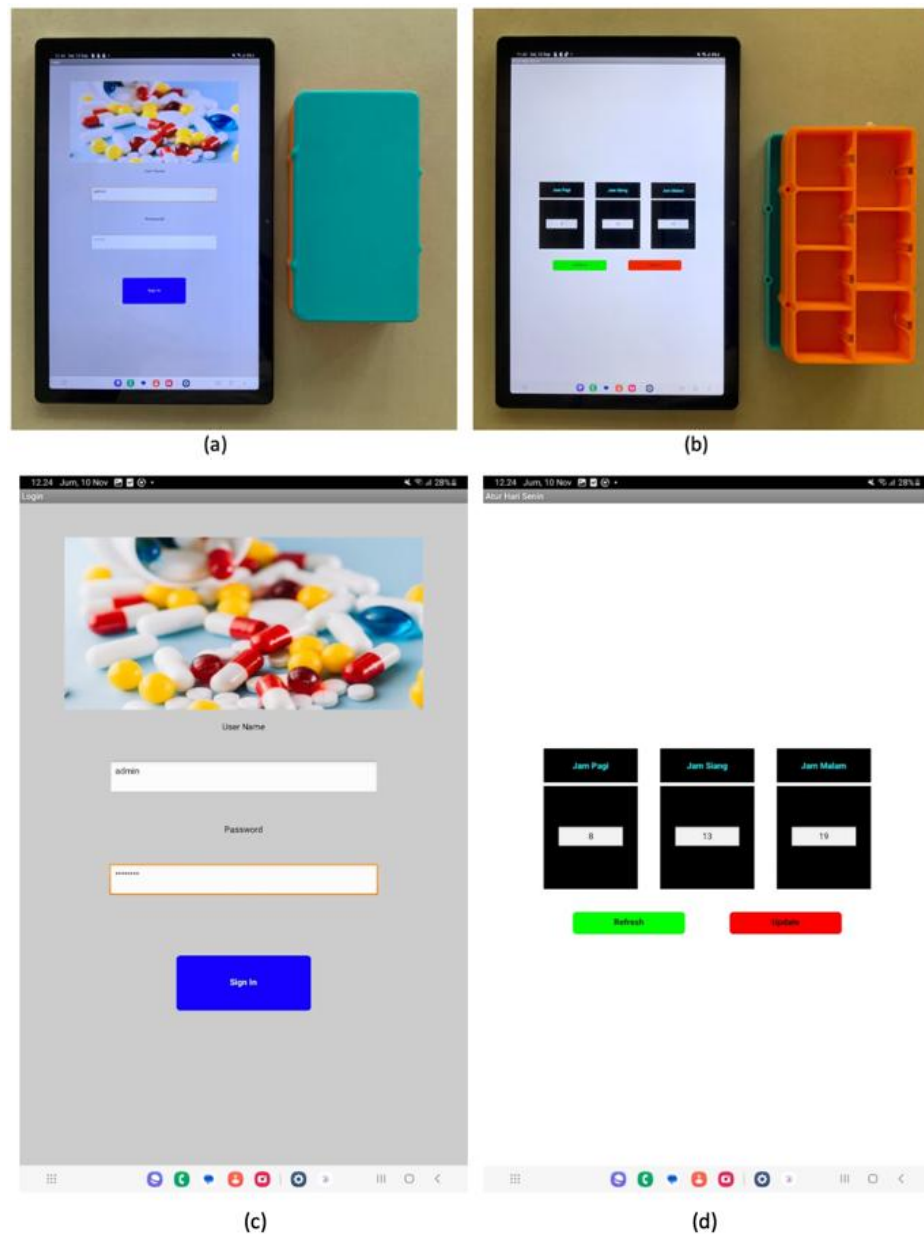


Figure 2 The prototype of small pill box (a, b) and user interface of smartphone app (c, d)

3.2 Study participants

Study participants were recruited through targeted outreach via the WhatsApp messaging platform, a widely used communication media that enabled the research team to engage with communities aligned with the study's inclusion criteria. These communities predominantly consisted of individuals seeking support and advice related to chronic medical conditions and healthcare management. To incentivize participation, an e-money reward of USD 30 was offered to each participant upon successful completion of the study, with the amount deposited into their preferred e-money accounts. This approach not only expedited the recruitment process but also enhanced the diversity and representativeness of the participant sample by reaching a broad demographic. Out of the 15 individuals approached, 10 met the inclusion criteria and consented to participate in the study. All these participants were subsequently engaged in a four-week evaluation of the prototype's functionality and efficacy. A comparative analysis was conducted between the levels of

the participant's self-reported adherence prior to device implementation and the adherence levels monitored by the system during the study. The demographic and other relevant details of the participants are summarized in Table 1.

Table 1 Demographic and clinical characteristics of the study participants (n=10)

Demographic Information	n (%)
Age (years old)	
a) 31 - 40	2 (20.00)
b) 41 - 50	5 (50.00)
c) 51 - 60	3 (30.00)
Gender	
a) Male	5 (50.00)
b) Female	5 (50.00)
Medical condition	
a) Hypertension	2 (20.00)
b) Diabetes	2 (20.00)
c) Asthma	2 (20.00)
d) Heart Disease	4 (40.00)
Duration of condition (years)	
a) 0 to 5	6 (60.00)
b) 6 to 10	4 (40.00)
Educational Background (Higher Education	
a) High School	2 (20.00)
b) Undergraduate	6 (60.00)
c) Postgraduate	2 (20.00)
Annual Income (US\$)	
a) 0 - 5000	6 (60.00)
b) 5001 - 10000	4 (40.00)
Daily Drug Intake	
a) 1	3 (30.00)
b) 2	4 (40.00)
c) 3	3 (30.00)
Smartphone Usage Frequency	
a) Daily	10 (100.00)
b) Weekly	0 (0.00)
c) Rarely	0 (0.00)

The demographic profile of the participants involved in this project provides a detailed overview of the cohort's characteristics. Age distribution represents that the majority of participants, accounting for 50% (n = 5), fall within the 41–50 age range. Approximately 30% (n = 3) are aged between 51–60 years old, while the remaining 20% (n = 2) are between 31–40 years. Gender representation is balanced, with equal proportions of males and females. An analysis of medical conditions confirms that heart disease is the most prevalent condition, affecting 40% (n = 4) of the participants, while hypertension, diabetes, and asthma each impact 20% (n = 2). Furthermore, a majority of participants, 60% (n = 6), have been managing their conditions for a shorter duration of 0–5 years, compared to 40% (n = 4) who have been managing their conditions for 6–10 years. In terms of educational attainment, two participants (20.0%) had completed high school, six participants (60.0%) held an undergraduate degree, and two participants (20.0%) held a postgraduate degree; no participants reported a diploma/associate qualification. This distribution reflects a predominantly degree-educated cohort (80.0%), while still including individuals without higher education (20.0%), enabling preliminary assessment of usability across basic and advanced educational strata. Income distribution demonstrates that 60% (n = 6) earn between \$0 and \$5,000 annually, while the remaining 40% (n = 4) have annual earnings ranging from \$5,001 to \$10,000. Regarding medication use, 40% (n = 4) of these participants are on a daily regimen of two drugs, while 30% (n = 3) take between one and three medications daily. Notably, the participants (100%; n = 10) report using smartphones daily, indicating a high degree of technological familiarity and engagement within the cohort.

3.3 Adherence rates before and after using smart pill box

The participant's adherence to prescribed medication regimens was quantitatively assessed through a systematic approach. The adherence rate was calculated using the following formula [24].

$$\text{Adherence rate} = \frac{\text{number of doses taken as prescribed}}{\text{total number of doses prescribed}} \times 100\%$$

In this calculation, the “number of doses taken as prescribed” corresponds to the recorded instances of medication intake, as recorded by the pill box. Conversely, the “total number of doses prescribed” reflects the number of doses which the participant was instructed to take throughout the study period. This adherence percentage was determined by dividing the actual doses consumed by the prescribed doses and multiplying the resulting quotient by 100. For instance, in a scenario where a user was prescribed a medication requiring administration twice daily over a four-week period (amounting to 56 doses) but consumed only 50 doses, the adherence rate would be computed as approximately 89.29%. The calculations were methodically performed for each participant, providing a detailed analysis of adherence patterns across the study cohort. These rates, both before and after the introduction of the pill box, are presented in Table 2, offering critical insights into the impact of this intervention on medication adherence.

Table 2 Participant's adherence rates before and after using the smart pill box (n=10)

Number of participants	Before study (%)	After 4-week trial (%)
1	80	90
2	76	88
3	78	95
4	77	93
5	80	94
6	79	92
7	75	90
8	78	91
9	77	94
10	79	93

Table 2 shows a detailed comparative analysis of medication adherence rates among 10 participants before and after the implementation of the pill box during a 4-week trial. Prior to the intervention, adherence rates ranged from 75% (Participant 7) to 80% (Participants 1 and 5), with an average pre-intervention rate of 77.9%. Following the deployment of the pill box, adherence rates improved markedly across all participants, with the majority achieving rates in the 90th percentile. The smallest improvement was found in Participant 2, with a post-intervention adherence rate of 88%, while the highest adherence rate of 95% was recorded for Participant 3. Post-trial data revealed an average adherence rate of 92%, representing a substantial increase compared to the baseline rates. Such findings underscore the efficacy of the pill box in enhancing medication adherence, suggesting its potential as an innovative and effective solution for addressing adherence challenges in clinical settings. The significant improvements in adherence, coupled with the device's user-friendly design and high rate of participant adoption, further reinforce its viability for widespread application in real-world healthcare scenarios.

3.4 Results of statistical tests on the score of medication adherence

The paired t-test was employed to evaluate differences in medication adherence scores before and after the implementation of the smart pill box intervention. To validate the normality assumption essential for the application of the paired t-test, the Shapiro-Wilk test was performed, particularly suitable for the small sample size in this study (n = 10). The results of the Shapiro-Wilk test (shown in Table 3) revealed no significant deviation from normality ($p > 0.05$), thus confirming the appropriateness of the paired t-test for this dataset. The significant p-value obtained from the paired t-test showed a notable improvement in medication adherence following the intervention, underlining the robustness of this approach within the context of the study's design and dataset.

Table 3 Shapiro-Wilk test for normality of differences in medication adherence scores

Variable	Significance
Medication Adherence Scores Differences	0.286

Note: A p-value greater than 0.05 indicates no significant departure from normality, justifying the use of parametric tests

Medication adherence scores were comprehensively evaluated using a paired sample test to measure the variation in adherence levels before and after implementing the app-driven smart pill box. This analysis, conducted with a sample size of 10 participants, yielded compelling results. As presented in Table 4, the test revealed a p-value of 0.001, substantially below the standard significance threshold of 0.05. This low p-value provides the robust evidence of a statistically significant enhancement in medication adherence following the deployment of the smart pill box. Additionally, the findings demonstrate the efficacy of integrating IoT and microcontroller systems within the prototype, indicating its capability to deliver meaningful improvements in patient adherence. The pronounced improvement in adherence scores highlights the functional effectiveness of the device and its promising potential as a transformative device in the healthcare domain, particularly for addressing challenges related to medication adherence.

The descriptive statistics revealed that the mean pre-intervention adherence rate was $77.9 \pm 1.66\%$, while the mean post-intervention adherence rate increased to $92.0 \pm 2.21\%$. This substantial improvement was confirmed by the paired t-test, which demonstrated a highly significant difference between the two conditions (t-value = 19.96; $p < 0.001$). The calculated effect size (Cohen's d = 6.31) indicates an exceptionally large effect, suggesting that the introduction of the IoT-enabled smart pill box produced a strong positive influence on medication adherence. These findings highlight not only the statistical significance but also the clinical relevance of the intervention, showing that even over a relatively short period, the device markedly improved participants' adherence to prescribed regimens. The combination of a high mean difference, narrow standard deviations, and a very large effect size further reinforces the robustness of the results, despite the small sample size.

Table 4 Results of paired sample t-test evaluating medication adherence scores before and after intervention

Variable	Mean $\pm$ SD*	Mean $\pm$ SD**	t-value	p-value	Cohen's d
Medication adherence (%)	77.9 ± 1.66	92.0 ± 2.21	19.96	<0.001	6.31

NOTE: *: Before intervention; **: After intervention

The intervention demonstrated a clear improvement in adherence rates. Quantitatively, the mean adherence increased from $77.9 \pm 1.66\%$ before the intervention to $92.0 \pm 2.21\%$ after the four-week trial. Statistical testing using a paired t-test confirmed that this improvement was highly significant (t-value = 19.96, $p < 0.001$). Importantly, the effect size was exceptionally large (Cohen's d = 6.31), underscoring the strength of the intervention's impact. Such a magnitude suggests that the observed improvements are not only statistically significant but also of substantial clinical importance. In the context of adherence research, where effect sizes are often modest due to multifactorial influences on patient behavior, this very large effect provides compelling preliminary evidence that IoT-enabled smart pill boxes may represent a transformative approach to managing chronic therapies.

These findings are consistent with prior studies reporting that technology-assisted adherence interventions can yield measurable benefits; however, the size of the effect in this study is particularly notable. For example, a study by Vervloet et al. (2012) reported adherence improvements of up to 81% with SMS-based reminders [25], whereas the present study demonstrated a nearly 39% absolute increase with a significantly stronger statistical effect [26]. This discrepancy may be attributed to the combination of real-time logging, dual alert mechanisms, and user-friendly smartphone integration, which together provide a more immersive and responsive adherence support system. Nevertheless, while these results are promising, they should be interpreted within the context of a small pilot sample and short duration. The large effect size may reflect the novelty and initial enthusiasm of participants (a potential Hawthorne effect) rather than a sustainable long-term change. Future research with larger and more diverse cohorts, extended follow-up periods (3–6 months or more), and inclusion of a control group will be necessary to confirm the durability and generalizability of these findings.

It is important to note that baseline adherence rates were self-reported, which may introduce minor overestimation when comparing pre- and post-intervention results. The use of self-reported data to establish baseline.

3.5 Feedback on the smart pill box usability

The evaluation of the pill box's efficacy, as assessed by 10 participants, found positive feedbacks, as detailed in Table 5. Most participants commended the system for its intuitive user interface, the effectiveness of LED light notifications, and the seamless synchronization between the app and the pill box. The device's alarm function was highly appreciated for ensuring timely medication reminders, while real-time medication journal received praise for its precise record-keeping capabilities. Additional feedbacks were directed toward the ergonomic design, the clarity of medication information displayed on the app, and the positive influence these features had on stimulating disciplined and timely medication administration. Collectively, such aspects underscored the device's value, particularly for individuals managing demanding schedules. Unfortunately, one participant (10%) reported occasional synchronization issues, showing a potential area for improvement in the system's integration. Despite minor limitation, 90% of the respondents expressed strong enthusiasm for continued use of the device, affirming its practicality and efficacy in supporting medication adherence.

Table 5 Participant's feedback on the smart pill box usability (n=10)

No.	User-Friendly (Yes/No)	Interest in Continued Use (Yes/No)	Feedback on System's Usability
1	Yes	Yes	Intuitive interface; easy to navigate.
2	Yes	Yes	Efficient reminders; liked the LED light notification.
3	Yes	Yes	App syncs well with the pill box.
4	No	No	Faced occasional syncing issues.
5	Yes	Yes	Alarm sound was a helpful reminder.
6	Yes	Yes	Appreciated the real-time medication log.
7	Yes	Yes	Found the overall design ergonomic and portable.
8	Yes	Yes	The app provided clear medication information.
9	Yes	Yes	Felt more disciplined with timely medication.
10	Yes	Yes	Useful for busy schedules; prevented missed doses.

Technological advancements, notably the integration of IoT technologies in healthcare sectors, have introduced transformative opportunities to enhance patient care and medication adherence strategies [27]. This study particularly aimed to address the persistent issue of medication non-adherence, widely recognized as a significant contributor to suboptimal patient outcomes and increased healthcare expenditures [28-30]. The proposed solution, smart pill box, focuses on the potential of combining IoT with microcontroller system to create innovative healthcare intervention. It achieved a 92% of adherence rate, demonstrating the tangible benefits of leveraging technology in promoting adherence. It also represents a notable improvement compared to the baseline self-reported adherence rate of 78%, a finding consistent with recent literature emphasizing the gap between actual adherence behaviors and patient-reported compliance. For instance, Ahmad et al. (2022) reported that while technological solutions improve measurement accuracy, comparisons between these rates often expose biases or inaccuracies inherent in self-reported data [31].

The overwhelmingly positive user feedback underscores the potential effectiveness of the prototype. Notably, 90% of involved participants endorsed its user-friendliness, a result that aligns with findings from a review by Jacob et al. (2020), which emphasized UI as a pivotal factor in the successful adoption of medical technology [32]. An intuitive interface not only promotes long-term engagement but also eases apprehensions that individuals may harbor towards advanced medical devices. The substantial interest in sustained system use suggests both a strong alignment with user requirements and broad demographic acceptability. However, as with any exploratory study, the findings must be contextualized within the limitations of research design. The optimistic results are derived from a relatively small sample size, rendering it premature to generalize the findings to larger populations. Future research involving larger and more diverse study samples—spanning a variety of medical conditions, age groups, and socioeconomic backgrounds—may uncover additional issues requiring consideration. This necessity for comprehensive trials prior to widespread implementation has been consistently advocated in prior studies [33-35].

The scalability potential of the pill box system is a very crucial consideration in its development and deployment. The current product is specifically designed with a capacity to hold 2 to 3 pills per compartment, a configuration that effectively meets the needs of patients with relatively straightforward daily medication regimens. The system's advanced app architecture improves versatility by enabling management of multiple compartments simultaneously, thereby optimizing UI for tracking and administering medications at different times or for various medication types. Notably, the system supports the parallel operation of multiple pill box devices, with each device configurable within the app to align with specific medication categories or dosing schedules. This flexibility is integral to the system's scalability, particularly for patients managing complex and extensive prescription schedules. Furthermore, the system's adaptability ensures that it can respond dynamically to the patient's evolving therapeutic needs, supporting increased complexity without sacrificing usability or efficiency. Such features underscore the pill box system's capacity to provide robust and scalable solutions for diverse medication adherence challenges. For polypharmacy, the app can assign multiple compartments to different medications and provide distinct alarms for each dosing schedule. For elderly users, future iterations will incorporate larger font sizes, voice reminders, and simplified navigation. Additionally, although this prototype was tested in adults aged 31–60 years, elderly patients

(>60 years) remain an important target group. Future trials will specifically enroll elderly participants to assess usability, accessibility, and cognitive load adaptation.

To validate these promising preliminary findings, future research should prioritize: (1) expanding the sample size to increase statistical power; (2) extending study duration to assess long-term adherence and engagement; (3) incorporating control groups to isolate the effect of the intervention; and (4) including elderly participants to evaluate usability across age groups. These steps are essential for translating this prototype into a scalable, evidence-based adherence solution.

3.6 Limitation of the study

Evaluation of the results from this study needs a careful acknowledgment of its inherent limitations. The most prominent limitation is the small sample size ($n = 10$), which significantly restricts the statistical power and generalizability of the findings. Additionally, the sample lacked demographic diversity — notably, it did not include participants over 60 years of age and consisted entirely of individuals who reported daily smartphone use, suggesting a tech-familiar population. These factors introduce potential bias and may overestimate adherence improvement, possibly influenced by novelty effects such as the Hawthorne effect. Future research should include a larger, more diverse participant pool and control for these confounding factors.

Another limitation concerns the use of self-reported data to establish baseline adherence. Such measures are inherently prone to recall and social desirability biases, potentially leading to overreporting of adherence and inflating the observed improvement. Future studies should incorporate objective measures—such as pharmacy refill records or electronic monitoring—to ensure more accurate baseline comparisons.

The 4-week duration of the trial provides only short-term insights into adherence and user engagement. This limited timeframe does not account for potential declines in adherence once the novelty of the device wears off. Long-term studies with follow-up periods of 3–6 months or more are necessary to assess the sustainability and continued usability of the smart pill box system. The reliance on self-reported data for establishing baseline medication adherence introduces the risk of recall bias, which may compromise the accuracy and comparability of the results. The digital orientation of the study further implies a possible bias toward participants who are more familiar with contemporary digital tools such as smartphones and IoT devices, potentially influencing their perceptions of system usability. Moreover, the current cohort did not include elderly participants (>60 years), who are often the most affected by non-adherence. This will be addressed in future research. Additionally, the limited sample size ($n=10$) restricts statistical power. Future trials will recruit at least 20–30 participants to validate accuracy and generalizability.

Another key limitation is the absence of a control group. Without a comparator, it is not possible to determine whether the observed improvement in adherence was due solely to the device or influenced by other factors, such as increased monitoring or participant motivation. This limits causal attribution. Future studies should adopt randomized controlled designs to rigorously evaluate the effectiveness of the smart pill box. As a prototype pilot project, there remains the possibility of undetected technical flaws or inefficiencies within the hardware or associated software. Internet connectivity, a critical component for real-time functionality, has not been evaluated under varying environmental conditions, leaving synchronization challenges unaddressed. The diversity of medication regimens among participants may also obscure detailed adherence behaviors related to regimen complexity. Additionally, baseline adherence relied on self-reported data, which may be affected by recall bias. Objective baseline measures, such as pharmacy refill data or electronic medication monitoring, should be considered in future trials. Furthermore, purposive sampling may introduce selection bias, favoring participants who are more technologically adept or open to digital interventions.

While these findings are encouraging, they should be interpreted as preliminary due to the study's limited sample size, short duration, and lack of a control group. The results demonstrate the potential of an IoT-enabled smart pill box to improve adherence, but more rigorous testing in larger, long-term, and controlled trials is necessary before broader conclusions can be drawn.

4. Conclusions

This pilot study practically provides promising preliminary evidence that an IoT- and microcontroller-based smart pill box may improve medication adherence and offer a user-friendly experience. However, given the small sample size, short trial duration, lack of a control group, and use of self-reported baseline data, these findings should be interpreted with caution. Future validation will require methodologically rigorous trials, including larger and more diverse populations, longer-term monitoring, inclusion of elderly patients, and control or comparison groups. These next steps are critical to fully understand the potential and limitations of this technology in real-world healthcare settings.

5. Acknowledgements

The authors thank the School of Pharmacy, Faculty of Medicine and Health Sciences, Universitas Muhammadiyah Yogyakarta, Indonesia and Faculty of Pharmacy, Mahidol University, Thailand for their invaluable assistance, resources, and unwavering support throughout this project.

6. References

- [1] Gu Y, Zalkikar A, Liu M, Kelly L, Hall A, Daly K, et al. Predicting medication adherence using ensemble learning and deep learning models with large scale healthcare data. *Sci Rep.* 2021;11(1):18961.
- [2] Ravens-Sieberer U, Kaman A, Erhart M, Otto C, Devine J, Löffler C, et al. Quality of life and mental health in children and adolescents during the first year of the COVID-19 pandemic: results of a two-wave nationwide population-based study. *Eur Child Adolesc Psychiatry.* 2023;32(4):575-88.
- [3] Gil-Guillen VF, Balsa A, Bernárdez B, Valdés y Llorca C, Márquez-Contreras E, de la Haba-Rodríguez J, et al. Medication non-adherence in rheumatology, oncology and cardiology: a review of the literature of risk factors and potential interventions. *Int J Environ Res Public Health.* 2022;19(19):12036.
- [4] Abdulsalim S, Unnikrishnan MK, Manu MK, Alrasheedy AA, Godman B, Morisky DE. Structured pharmacist-led intervention programme to improve medication adherence in COPD patients: a randomized controlled study. *Res Social Adm Pharm.* 2018;14(10):909-14.

- [5] Jeminiwa R, Hohmann L, Qian J, Garza K, Hansen R, Fox BI. Impact of eHealth on medication adherence among patients with asthma: a systematic review and meta-analysis. *Respir Med*. 2019;149:59-68.
- [6] Car J, Tan WS, Huang Z, Sloot P, Franklin BD. eHealth in the future of medications management: personalisation, monitoring and adherence. *BMC Med*. 2017;15(1):73.
- [7] Mistry N, Keepanasseril A, Wilczynski NL, Nieuwlaat R, Ravall M, Haynes RB, et al. Technology-mediated interventions for enhancing medication adherence. *J Am Med Inform Assoc*. 2015;22(e1):e177-93.
- [8] Chun-Yun Kang G. Technology-based interventions to improve adherence to antihypertensive medications—an evidence-based review. *Digit Health*. 2022;8:1-16.
- [9] Wagan SA, Koo J, Siddiqui IF, Attique M, Shin DR, Qureshi NMF. Internet of medical things and trending converged technologies: a comprehensive review on real-time applications. *J King Saud Univ - Comput Inf Sci*. 2022;34(10):9228-51.
- [10] Baker SB, Xiang W, Atkinson I. Internet of things for smart healthcare: technologies, challenges, and opportunities. *IEEE Access*. 2017;5:26521-44.
- [11] Alahi MEE, Sukkuea A, Tina FW, Nag A, Kurdthongmee W, Suwannarat K, et al. Integration of IoT-enabled technologies and artificial intelligence (AI) for smart city scenario: recent advancements and future trends. *Sensors*. 2023;23(11):5206.
- [12] Arshed M, Mahmud AB, Minhat HS, Ying LP, Umer MF. Effectiveness of mHealth interventions in medication adherence among patients with cardiovascular diseases: a systematic review. *Diseases*. 2023;11(1):41.
- [13] Atolagbe ET, Sivanandy P, Ingle PV. Effectiveness of educational intervention in improving medication adherence among patients with diabetes in Klang Valley, Malaysia. *Front Clin Diabetes Healthc*. 2023;4:1-11.
- [14] Shariful Islam SM, Mishra V, Siddiqui MU, Moses JC, Adibi S, Nguyen L, et al. Smartphone apps for diabetes medication adherence: systematic review. *JMIR Diabetes*. 2022;7(2):e33264.
- [15] Georgieva N, Tenev V, Kamusheva M, Petrova G. Diabetes mellitus—digital solutions to improve medication adherence: scoping review. *Diabetology*. 2023;4(4):465-80.
- [16] Smith JC, Seage CH, Lane E, James DH. Using the theoretical domains framework to determine the barriers and facilitators to medication adherence in Parkinson's disease. *Explor Res Clin Soc Pharm*. 2023;11:100309.
- [17] Islam T, Hassan R, Romy SR, Dellal D, Bin TRA. Enhancing medication adherence with IoT technology. *Eur J Electr Eng Comput Sci*. 2023;7(5):7-13.
- [18] Hui CY, McKinstry B, Fulton O, Buchner M, Pinnock H. Patients' and clinicians' visions of a future internet-of-things system to support asthma self-management: mixed methods study. *J Med Internet Res*. 2021;23(4):e22432.
- [19] Mohammed BG, Hasan DS. Smart healthcare monitoring system using IoT. *Int J Interact Mob Technol*. 2023;17(1):141-52.
- [20] Antoun W, Abdo A, Al-Yaman S, Kassem A, Hamad M, El-Moucary C. Smart Medicine Dispenser (SMD). 2018 IEEE 4th Middle East Conference on Biomedical Engineering (MECBME); 2018 Mar 28-30; Tunis, Tunisia. USA: IEEE; 2018. p. 20-3.
- [21] Kassem A, Antoun W, Hamad M, El-Moucary C. A comprehensive approach for a smart medication dispenser. *Int J Comput Digit Syst*. 2019;8(2):131-41.
- [22] Chan AHY, Harrison J, Black PN, Mitchell EA, Foster JM. Using electronic monitoring devices to measure inhaler adherence: a practical guide for clinicians. *J Allergy Clin Immunol Pract*. 2015;3(3):335-49.e1-5.
- [23] Kim SK, Park SY, Hwang HR, Moon SH, Park JW. Effectiveness of mobile health intervention in medication adherence: a systematic review and meta-analysis. *J Med Syst*. 2025;49(1):13.
- [24] Ghazali MT. Assessing ChatGPT's accuracy and reliability in asthma general knowledge: implications for artificial intelligence use in public health education. *J Asthma*. 2025;62(6):975-83.
- [25] Vervloet M, van Dijk L, Santen-Reestman J, van Vlijmen B, van Wingerden P, Bouvy ML, et al. SMS reminders improve adherence to oral medication in type 2 diabetes patients who are real time electronically monitored. *Int J Med Inform*. 2012;81(9):594-604.
- [26] Regan AK, Bloomfield L, Peters I, Effler PV. Randomized controlled trial of text message reminders for increasing influenza vaccination. *Ann Fam Med*. 2017;15(6):507-14.
- [27] Li C, Wang J, Wang S, Zhang Y. A review of IoT applications in healthcare. *Neurocomputing*. 2024;565:127017.
- [28] Leving MT, van Boven JFM, Bosnic-Anticevich SZ, van Cooten J, Correia de Sousa J, Cvetkovski B, et al. Suboptimal peak inspiratory flow and critical inhalation errors are associated with higher COPD-related healthcare costs. *Int J Chron Obstruct Pulmon Dis*. 2022;17:2401-15.
- [29] Haitaamar Z, Sulaiman A, Bendoukha SA, Rodrigues D. Lower inclination orbit concept for direct-communication-to-satellite internet-of-things using lean satellite standard in near-equatorial regions. *Appl Sci*. 2023;13(9):5654.
- [30] Sharma A, Kaur J, Singh I. Internet of Things (IoT) in pharmaceutical manufacturing, warehousing, and supply chain management. *SN Comput Sci*. 2020;1(4):232.
- [31] Ahmad HS, Yang AI, Basil GW, Welch WC, Wang MY, Yoon JW. Towards personalized and value-based spine care: objective patient monitoring with smartphone activity data. *J Spine Surg*. 2022;8(1):87-92.
- [32] Jacob C, Sanchez-Vazquez A, Ivory C. Social, organizational, and technological factors impacting clinicians' adoption of mobile health tools: systematic literature review. *JMIR Mhealth Uhealth*. 2020;8(2):e15935.
- [33] Reiss F, Meyrose AK, Otto C, Lampert T, Klasen F, Ravens-Sieberger U. Socioeconomic status, stressful life situations and mental health problems in children and adolescents: results of the German BELLA cohort-study. *PLoS One*. 2019;14(3):e0213700.
- [34] Yoosefi Lebni J, Mohammadi Gharehghani MA, Soofizad G, Khosravi B, Ziapour A, Irandoost SF. Challenges and opportunities confronting female-headed households in Iran: a qualitative study. *BMC Womens Health*. 2020;20(1):183.
- [35] Ravens-Sieberger U, Kaman A, Erhart M, Devine J, Schlack R, Otto C. Impact of the COVID-19 pandemic on quality of life and mental health in children and adolescents in Germany. *Eur Child Adolesc Psychiatry*. 2022;31(6):879-89.