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Smart-ART: Enhancing HIV Medication Adherence in Pregnant Women with IoT-Enabled Medication Boxes

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ABSTRACT

Background: HIV testing and antiretroviral therapy (ART) coverage among pregnant women living with HIV in Indonesia remain suboptimal. Inadequate ART adherence may compromise treatment effectiveness and viral suppression, potentially increase the risk of mother-to-child HIV transmission and highlighting the need for technology-assisted adherence monitoring.
Aims: This study aimed to develop Smart-ART and assess its technical functionality and preliminary feasibility for monitoring ART adherence among pregnant women living with HIV.
Methods: Smart-ART was developed using the Rapid Application Development (RAD) approach. The system comprised an IoT-enabled medication box, a patient-facing mobile application, and a provider-facing telemonitoring interface. Technical functionality was assessed through functional testing. A 30-day pilot pre–post evaluation was subsequently conducted among 15 pregnant women living with HIV receiving ART at an urban community health center. ART adherence was operationalized as the proportion of scheduled medication events completed within one hour of the initial medication reminder, supported by photographic confirmation and review by HIV care coordinators.
Results: Among the 15 participants, mean ART adherence was 70.0% at baseline and 96.2% after 30 days of Smart-ART use, corresponding to a mean increase of 26.2 percentage points ($p < 0.001$). All participants showed higher adherence during the Smart-ART period than at baseline. Functional testing demonstrated that the system generated scheduled medication reminders through the pillbox and application and enabled participants to submit photographic evidence of medication intake for review by HIV care coordinators. The provider interface enabled remote access to medication-event records and adherence status. Intermittent internet connectivity was identified as an implementation limitation that may affect continuous telemonitoring and data synchronization.
Conclusion: Smart-ART demonstrated technical feasibility and was associated with improved ART adherence in this 30-day pilot evaluation. The single-arm pre–post design, small sample, short follow-up, and single healthcare setting limit causal inference and generalizability. Larger controlled studies with longer follow-up are

needed to determine clinical effectiveness, usability, scalability, and implementation feasibility.

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1. Introduction

Indonesia ranks among the countries with the highest rates of mother-to-child HIV transmission globally (Siregar *et al.,* 2021). This issue poses a significant challenge to achieving the goal of Ending AIDS in Indonesia by 2030 (Chilaka & Konje, 2021; Nurmisih *et al.,* 2022). Although Indonesia mandates that all pregnant women undergo HIV testing during their first antenatal care (ANC) visit (Inzaule *et al.,* 2018), the performance of HIV test-and-treat services for pregnant women remains low (Al Adawiyah *et al.,* 2022). In 2017, while ANC service coverage was high—95.4% for the first visit (K1) and 87.3% for the fourth visit (K4)—HIV testing coverage for pregnant women was only 28%, and Antiretroviral (ARV) treatment coverage was a mere 13%. These missed opportunities fall far short of the expected Prevention of Mother-to-Child Transmission (PMTCT) targets and the WHO 95/95/95 goal, which aims for 95% of pregnant women to attend antenatal care, 95% to undergo HIV testing, and 95% of those diagnosed with HIV to receive immediate treatment (Wariki *et al.,* 2017; World Health Organization, 2022).

The challenges of ARV therapy performance are not limited to HIV-positive pregnant women but also extend to low adherence to ARV therapy itself (Zewude & Ajebe, 2022). Adherence to ARV therapy is critical for ensuring the effectiveness of HIV treatment and improving the quality of life for patients (Abadiga *et al.,* 2020; Hansana *et al.,* 2013). ARVs control the amount of HIV in the patient's body, allowing the immune system to function more effectively. Strict adherence to ARV therapy enables HIV patients to live longer and enjoy a better quality of life (Armini *et al.,* 2023; Siregar *et al.,* 2020). However, adherence remains a significant challenge due to the necessity of taking medication daily on a fixed schedule (Iacob *et al.,* 2017). Timely medication intake is a crucial factor affecting therapy success, as delays or missed doses can lead to viral resistance, reducing the effectiveness of ARVs and increasing the risk of HIV transmission (Carr *et al.,* 2023).

Various factors influence adherence, including social, economic, and psychological factors. For instance, lack of social support from family or friends (Moomba & van Wyk, 2019), emotional challenges such as stress and depression (Msefula & Umar, 2024), and financial constraints (Fauk *et al.,* 2022), can all impact adherence to ARV therapy. To address adherence issues, healthcare professionals can provide education on the importance of adherence, assist patients in gaining social support, and ensure access to medication and routine check-ups (Lumbantoruan *et al.,* 2018). In addition to medical interventions, digital technology advancements, particularly Internet of Things (IoT) applications within the Internet of Health Things (IoHT) framework, offer effective solutions for enhancing ARV adherence among HIV patients (Kaya *et al.,* 2021; Petersen *et al.,* 2007). These technologies can provide automatic reminders, monitor medication consumption in real-time, and enable remote monitoring for healthcare providers and HIV management programs.

This study aims to develop Smart-ART, an IoT-based smart pillbox designed to support ART adherence among pregnant women with HIV. Smart-ART also features telemonitoring capabilities, enabling healthcare providers or HIV program coordinators at primary healthcare centers to remotely monitor patient adherence levels. This innovative approach aims to improve ART adherence among HIV-positive pregnant women, ultimately contributing to national and global health goals by reducing mother-to-child HIV transmission.

2. Methods

This study developed Smart-ART, an Internet of Things (IoT)-based medication box designed to support antiretroviral therapy (ART) adherence monitoring among pregnant women living with HIV. The study consisted of two main components: (1) development and technical testing of the Smart-ART prototype and (2) a 30-day pilot pre–post evaluation of ART adherence. The prototype was developed using the Rapid Application Development (RAD) approach, which supports iterative development and evaluation of system components (Pratiwi *et al.,* 2022; Nurhayati *et al.,* 2022). The development process comprised system requirements determination, system design, material selection, production, connectivity and system testing, and functional testing.

2.1 Study Setting and Participants

The pilot evaluation was conducted at an urban community health center among pregnant women living with HIV who were receiving ART. A total of 15 pregnant women living with HIV participated in the 30-day pilot trial. The Smart-ART system was designed for two user groups: pregnant women living with HIV as patients and HIV program coordinators at primary healthcare centers as healthcare providers. The 15 pregnant women were the participants in the pilot adherence evaluation, whereas HIV program coordinators were involved in monitoring medication-event records and adherence information through the provider interface.

Participants used the Smart-ART system continuously for 30 days. During the pilot period, medication reminders were configured at three fixed times each day: 06:00, 15:00, and 21:00. These reminder times were applied consistently to all participants in this pilot study. Although the patient application included a medication-scheduling interface, the schedule used in the evaluated pilot was fixed at these three medication times.

2.2 System Requirements Determination

System requirements were identified through interviews with HIV specialists and discussions with healthcare professionals. The requirements focused on the medication-storage capacity, physical dimensions, medication-reminder mechanism, medication-event monitoring, mobile application functionality, and remote monitoring requirements. The requirements determination stage also considered accessibility and practical use of the medication box for pregnant women living with HIV. The resulting requirements were subsequently used as the basis for the design and development of the Smart-ART prototype.

2.3 Smart-ART System Design

Smart-ART consisted of three main components: an IoT-enabled medication box, a patient-facing mobile application, and a provider-facing telemonitoring interface. The medication box communicated with the mHealth system through Wi-Fi connectivity. The medication box used a LOLIN/Wemos D1 Mini Pro based on the ESP8266 microcontroller as the main controller. The hardware configuration included an OLED display, DS3231 Real-Time Clock (RTC), buzzer, medication-related sensor(s), 18650 rechargeable battery with charging/discharging module, and Wi-Fi connectivity. The DS3231 RTC was used to provide the time reference for scheduled medication reminders. The OLED display provided visual information to the user, while the buzzer provided an audible medication reminder. Medication-related sensor(s) were incorporated to detect medication-related events and support medication-event recording. The exact sensor model/type was not specified in the available study documentation and is therefore not further identified in this manuscript.

The patient application was developed for Android smartphones. The application included user authentication, a home interface, medication scheduling, medication logs, and a mechanism for

submitting photographic evidence of medication intake. The provider-facing interface enabled HIV program coordinators to remotely access medication-event records and adherence information. The data flow of the system comprised medication scheduling, reminder generation, medication-event recording, transmission through the IoT/mHealth infrastructure, and presentation of adherence information through the provider interface.

2.4 Medication Box Design and Material Selection

The Smart-ART medication box was designed with six separate medication compartments and overall dimensions of 6.3 cm × 4.4 cm × 1.9 cm. The six compartments were intended to accommodate medication supplies for six days. The physical enclosure was fabricated using acrylic/3D-printed components. The design incorporated visual elements, including batik-themed illustrations on the compartment covers, as part of the visual design of the prototype. The physical design emphasized compact dimensions and accessibility of the medication compartments (Nasir *et al.,* 2023). Formal usability, durability, portability, medication-stability, and material-compatibility testing were not conducted as separate outcome assessments in this study.

2.5 Medication Reminder and IoT Communication

The medication reminder mechanism used the DS3231 RTC to determine the scheduled medication times. At the predefined reminder times of 06:00, 15:00, and 21:00, the system activated the buzzer and displayed a medication reminder on the OLED display. The representative program logic used the current RTC time to compare the hour and minute with the predefined reminder schedule. When the scheduled time was reached, the buzzer was activated for 1 second, after which it was turned off and the medication reminder message was displayed on the OLED interface.

The Smart-ART prototype used Wi-Fi connectivity to communicate with the mHealth server. The system architecture supported the exchange of medication-event and adherence information between the medication box, patient application, server infrastructure, and provider monitoring interface. The Smart Box-ART communicated periodically with the mHealth server at five-second intervals. This communication interval was distinct from the local medication reminder mechanism, in which the buzzer was activated for one second at the predefined medication time.

2.6 Functional Testing

Functional testing was conducted after completion of the Smart-ART prototype to verify the operation of the main system functions. The testing involved healthy individuals and focused on technical functionality rather than clinical effectiveness. The functional assessment included verification of the medication reminder mechanism, display output, medication-event recording, mobile application functionality, photographic evidence submission, and provider-side access to adherence information (Minaam & Abd-ELfattah, 2018; Rosli & Husaini, 2018).

The reminder function was considered operational when the predefined medication schedule triggered the corresponding audible and visual reminder. The mobile application was assessed for its ability to receive medication-related information and support submission of photographic evidence. The provider interface was assessed for its ability to display medication-event and adherence records remotely. Because the study did not use a formal usability scale or predefined usability-performance thresholds, the functional testing results were interpreted as evidence of technical operation rather than formal usability validation.

2.7 Electrical Output Testing

An electrical output test was conducted to characterize the voltage across the buzzer of the Smart-ART medication box under two operating states: OFF and ON. Voltage measurements were performed

using a Fluke 17B+ Digital Multimeter. Three repeated measurements were obtained for each operating state under the same test conditions. The measured OFF-state voltages were 66 mV, 19 mV, and 22 mV, whereas the ON-state voltages were 3.192 V, 3.196 V, and 3.197 V. The mean voltage was calculated separately for the OFF and ON states. The measurements were used to characterize the electrical output of the buzzer during prototype operation. The repeated measurements were compared descriptively to assess the consistency of the measured buzzer voltage. This test was intended to characterize electrical output and was not considered a comprehensive assessment of electrical safety or long-term system reliability.

2.8 Pilot Pre–Post Evaluation

Following technical testing, a 30-day pilot pre–post evaluation was conducted among 15 pregnant women living with HIV receiving ART at an urban community health center. ART adherence was operationalized specifically for this study as the proportion of scheduled medication events in which medication intake occurred within a maximum of one hour after the initial medication reminder. Medication intake was supported by photographic evidence submitted through the patient application and reviewed by HIV care coordinators. The denominator for adherence calculation was the total number of scheduled medication events during the observation period, while the numerator represented scheduled medication events completed within the predefined one-hour adherence window. Adherence was defined as medication intake completed within a maximum of one hour after the initial medication reminder, supported by photographic evidence. The adherence measure incorporated the timing of medication intake in addition to whether the prescribed dose was taken. This operational definition differs from conventional adherence measures that calculate adherence primarily from the number of doses reported as taken relative to the total number of prescribed doses (Fedlu *et al.*, 2020; Terefe *et al.*, 2021). Thus, adherence was calculated as explained in Equation (1).

$$ART\ Adherence\ (\%) = \frac{Number\ of\ medication\ events\ completed\ within\ the\ predefined\ one-hour\ window}{Total\ scheduled\ medication\ events} \times 100 \quad (1)$$

This operational definition represents a timing-based adherence measure used in the Smart-ART pilot and should not be interpreted as equivalent to broader clinical definitions of ART adherence or viral suppression.

2.9 Statistical Analysis

ART adherence measurements were paired within participants because adherence was assessed before and after Smart-ART use. Given the small sample size (n = 15) and paired nature of the observations, the Wilcoxon signed-rank test was used to compare ART adherence before and after the 30-day Smart-ART trial. Statistical significance was assessed using a two-sided significance level of $\alpha = 0.05$. The resulting p-value was interpreted as evidence of a statistical difference between the paired adherence measurements, rather than as definitive evidence of a causal treatment effect, because the pilot evaluation did not include a randomized control group.

2.10 Ethical Consideration

Participants provided consent for the use of their research data. The data-use documentation stated that participant information would be maintained confidentially and anonymously and would be used solely for research purposes. No formal institutional ethical clearance was obtained for this pilot evaluation. Accordingly, the findings are presented as a preliminary pilot evaluation, and no claim of formal ethical approval is made.

3. Results and Discussions

3.1 Smart-ART System Design

The Smart-ART system comprised three main components: an IoT-enabled medication box, a patient-facing mobile application, and a provider-facing telemonitoring interface. The medication box was designed to provide scheduled medication reminders and to record medication-related events. The patient application supported medication scheduling, medication logs, and submission of photographic evidence of medication intake. The provider interface enabled HIV program coordinators to remotely access medication-event records and adherence information. Figure 1 illustrates the Smart-ART system workflow, including the data flow between the medication box, patient application, mHealth server, and provider monitoring interface. The workflow incorporates medication schedules, reminder signals, medication-event records, and photographic evidence submitted through the patient application.

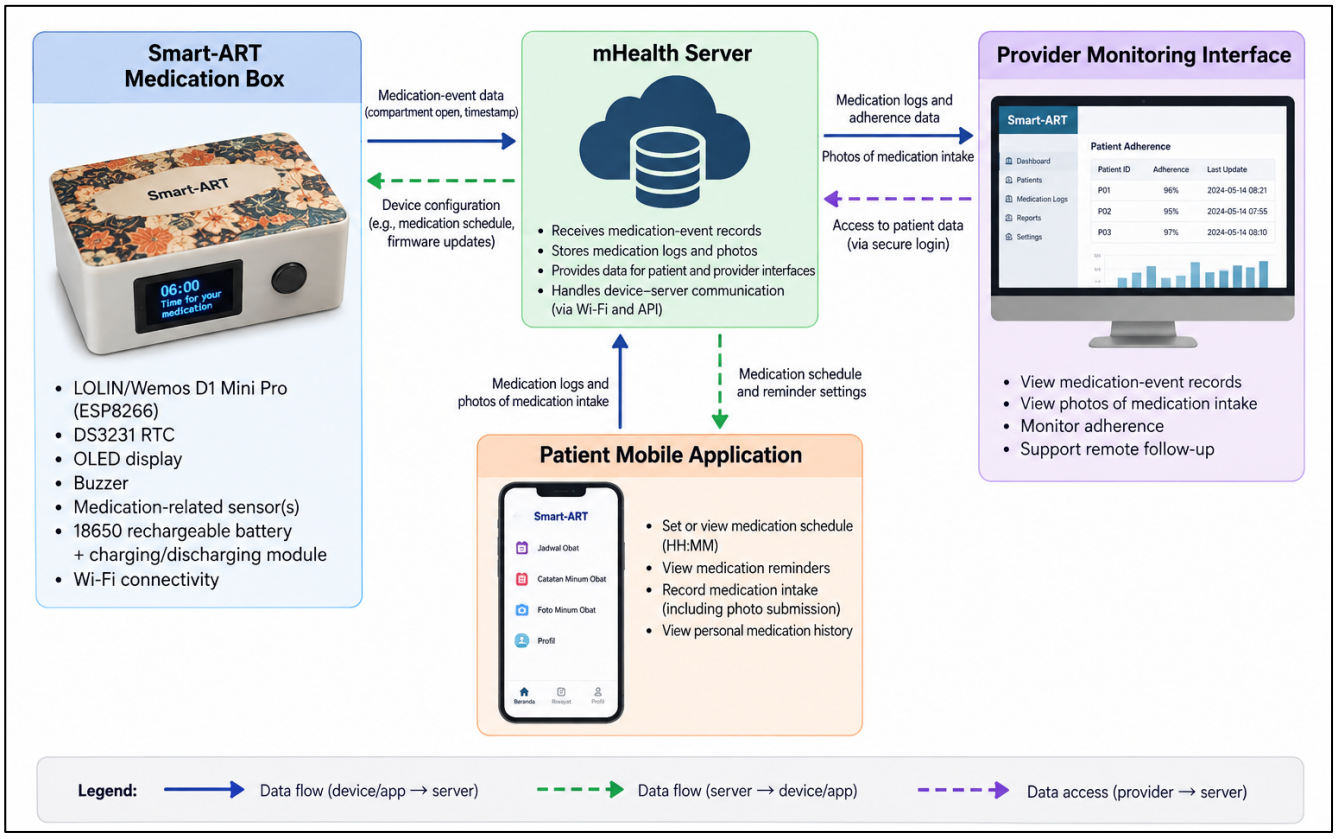


Figure 1. Smart-ART system workflow and data flow.

3.2 Patient and Provider Interfaces

The Smart-ART application included a login interface, a home interface, a medication-scheduling interface, and a medication-log interface (Figure 2). The medication-scheduling interface allowed medication times to be entered using the HH:MM format. The interface was presented in Bahasa Indonesia to accommodate the intended Indonesian user population. The interface used a concise menu structure and simplified navigation for medication scheduling and review of medication records. These features represent design characteristics of the prototype; formal usability, user experience, or cognitive-burden assessments were not conducted in this study.

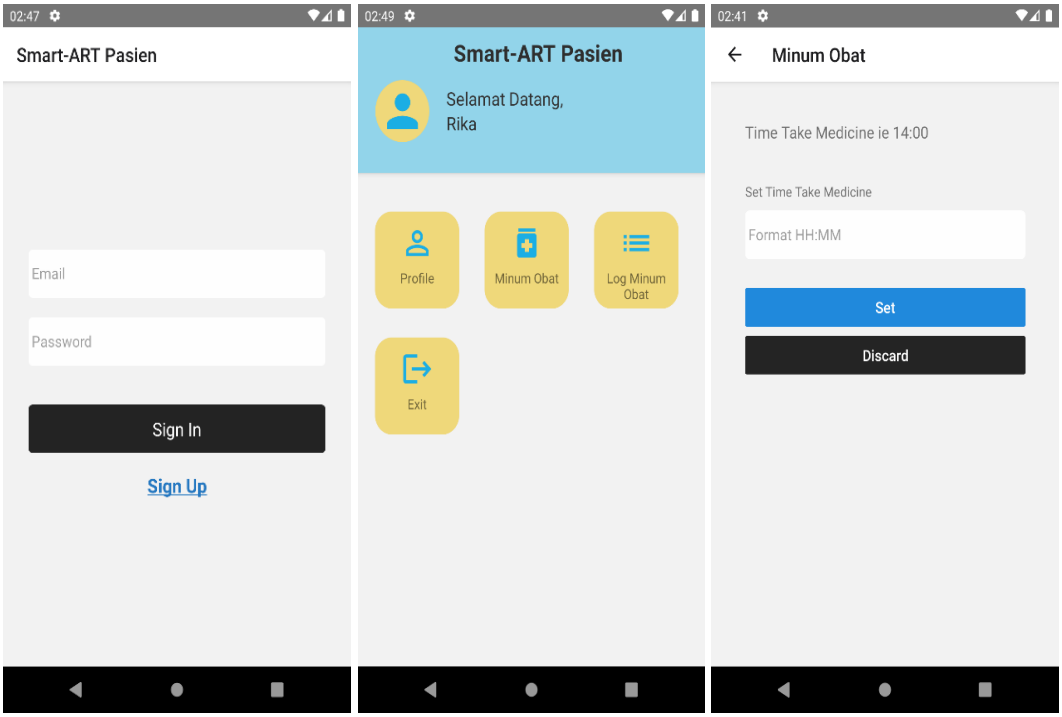


Figure 2. Smart-ART mobile application user interface in Bahasa Indonesia.

3.3 IoT-Enabled Medication Box

The Smart-ART medication box consisted of six separate medication compartments and measured 6.3 cm × 4.4 cm × 1.9 cm. The prototype was fabricated using acrylic/3D-printed components. The IoT hardware integrated a LOLIN/Wemos D1 Mini Pro based on the ESP8266 microcontroller, an OLED display, a DS3231 RTC, a buzzer, medication-related sensor(s), an 18650 rechargeable battery with charging/discharging module, and Wi-Fi connectivity. The DS3231 RTC provided the time reference for scheduled medication reminders. The OLED display provided visual feedback, while the buzzer generated the audible medication reminder. Medication-related sensor(s) were incorporated to support medication-event detection. The device communicated with the mHealth infrastructure through Wi-Fi connectivity. The six compartments were designed to accommodate a six-day medication supply. In the evaluated pilot, medication reminders were configured at 06:00, 15:00, and 21:00 for all participants. Figure 3 presents the Smart-ART medication circuit layout.

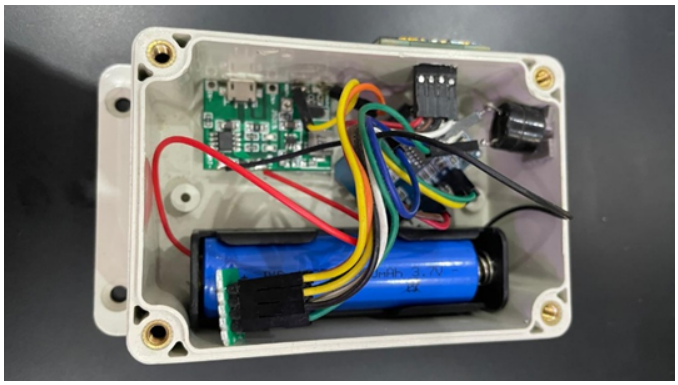


Figure 3. Smart-ART medication box circuit layout.

3.4 Reminder Control Logic

The Smart-ART reminder logic used the DS3231 RTC to determine the current time and compare it with the predefined medication schedule. In the pilot evaluation, reminders were configured at 06:00, 15:00, and 21:00. When the current time matched a scheduled reminder time, the buzzer was activated for 1 second, after which it was turned off and the OLED displayed a medication reminder message. Figure 4 presents a representative source-code snippet illustrating the local reminder logic. The code demonstrates RTC-based time retrieval, comparison with the predefined reminder schedule, buzzer activation, and OLED display output. The complete source code, including initialization and communication functions, is not presented in figure 4.

```
void loop() {
  // Gets the current time
  DateTime now = rtc.now();
  // Displays time on 128x64 LCD
  u8g2.clearBuffer();  // Clears buffers
  u8g2.setFont(u8g2_font_ncenB08_tr); // Set font
  u8g2.setCursor(0, 10);
  u8g2.print("Time: ");
  u8g2.print(now.hour());
  u8g2.print(":");
  if (now.minute() < 10) {
    u8g2.print("0");
  }
  u8g2.print(now.minute());
  u8g2.sendBuffer();  // Sends buffer to screen
  // Check if the current time matches the reminder clock
  for (int i = 0; i < 3; i++) {
    if (now.hour() == remindHours[i] && now.minute() ==
  remindMinute) {
      // Turn on the buzzer when the reminder time arrives
      digitalWrite(buzzerPin, HIGH);
      delay(1000); // The buzzer turns on for 1 second
      digitalWrite(buzzerPin, LOW);
      // Displays a reminder message on the LCD
      u8g2.clearBuffer();
      u8g2.setFont(u8g2_font_ncenB08_tr); // Set font
      u8g2.setCursor(0, 20);
      u8g2.print("Medicine Time!");
      u8g2.sendBuffer();  // Sends buffer to screen
      // Wait 60 seconds to prevent the reminder from repeating
  within 1 minute
      delay(60000);
    }
  }
  // Wait 1 second before checking again
  delay(1000);
}
```

Figure 4. Representative source code snippet illustrating the medication reminder logic of the Smart-ART medication box

3.5 Prototype Production

The fabricated Smart-ART prototype incorporated six medication compartments within an enclosure measuring 6.3 cm × 4.4 cm × 1.9 cm. The enclosure was fabricated using acrylic/3D-printed components and integrated the electronic control system described above. The six compartments were intended to accommodate medication supplies for six days. The physical design incorporated access to the medication compartments and visual design elements, including batik-themed illustrations on the compartment covers. The prototype dimensions and physical configuration were documented as part of the development process. However, formal tests of durability, device weight, portability, medication stability, and material compatibility were not conducted in this study (see Figure 5).



Figure 5. Smart-ART prototype production result.

3.6 Functional and Electrical Testing

Functional testing was conducted to verify the operation of the main Smart-ART functions. The tests confirmed that the medication box generated scheduled audible and visual reminders, while the patient application supported medication-related data entry and submission of photographic evidence. The provider interface enabled access to medication-event records and adherence information. The reminder function was tested using the predefined medication schedule of 06:00, 15:00, and 21:00. The buzzer was activated for 1 second when the scheduled time was reached, while the OLED displayed the medication reminder message. The functional testing demonstrated operation of the reminder mechanism under the tested conditions. The Smart-ART system also used Wi-Fi communication with the mHealth server. The system architecture supported periodic server communication and remote access to medication-event records. However, the available functional testing data did not include a quantitative assessment of network reliability, transmission success rate, or synchronization latency.

The electrical output measurements showed that the voltage across the buzzer in the OFF state ranged from 19 to 66 mV, with a mean of 35.67 mV. In the ON state, the measured voltage ranged from 3.192 to 3.197 V, with a mean of 3.195 V. The ON-state measurements differed by only 5 mV across the three repeated measurements, indicating consistent buzzer voltage output under the tested conditions. These measurements characterize the electrical output of the buzzer during prototype operation. They should not be interpreted as evidence of comprehensive device safety or long-term system reliability because additional electrical, thermal, battery, and durability assessments were not conducted. The results of the buzzer voltage measurement test are presented in Table 1.

Table 1. Buzzer electrical output measurements using a Fluke 17B+ Digital Multimeter

Test(s)	Buzzer OFF (mV)	Buzzer ON (V)
1	66	3.192
2	19	3.196
3	22	3.197
Mean	35.67	3.195

The electrical output measurements showed that the voltage across the buzzer in the OFF state ranged from 19 to 66 mV, with a mean of 35.67 mV. In the ON state, the measured voltage ranged from 3.192 to 3.197 V, with a mean of 3.195 V. The ON-state measurements differed by only 5 mV across the three repeated measurements, indicating consistent buzzer voltage output under the tested conditions. These measurements characterize the electrical output of the buzzer during prototype operation. However, the results should not be interpreted as evidence of comprehensive device safety or long-term system reliability, because additional electrical, thermal, battery, and durability assessments were not conducted.

3.7 Pilot Trial and Time-Deviation Analysis

A 30-day pilot trial was conducted among 15 pregnant women living with HIV. During the observation period, the system recorded medication-related events and the corresponding medication-taking time. The reported average daily time deviation ranged from approximately 5.00 to 5.40 minutes among participants. These values indicate that the recorded medication events occurred relatively close to the scheduled medication times during the pilot period. However, the available analysis was based on summarized daily deviation values rather than event-level aggregation. Therefore, the time-deviation results should be interpreted descriptively and should not be considered a direct measure of cumulative medication-taking delay.

3.8 ART Adherence Evaluation

A 30-day pilot pre–post evaluation involving 15 pregnant women living with HIV was conducted to assess ART adherence before and after Smart-ART use. ART adherence was operationalized as the proportion of scheduled medication events completed within one hour after the initial medication reminder, supported by photographic evidence of medication intake. As shown in Table 2, mean adherence was 70.0% before Smart-ART use and 96.2% during the Smart-ART trial, corresponding to an absolute difference of 26.2 percentage points. Individual adherence values after Smart-ART use ranged from 95% to 97%, compared with 68% to 73% at baseline. All 15 participants had a higher adherence value during the Smart-ART period than at baseline. The paired observations were analyzed using the Wilcoxon signed-rank test, which indicated a statistically significant difference between the two measurement periods ($p < 0.001$). The observed difference represents an association between the Smart-ART trial period and adherence in this pilot sample. Because the study used a single-arm pre–post design without a randomized control group, the statistical difference should not be interpreted as definitive evidence that Smart-ART caused the observed improvement.

Table 2. ART adherence before and after Smart-ART implementation

Participant ID	Adherence Before Smart-ART (%)	Adherence After Smart-ART (%)
P01	70	96
P02	68	95
P03	71	96
P04	69	96
P05	71	97
P06	72	96

P07	69	97
P08	70	95
P09	68	95
P10	70	97
P11	71	96
P12	69	97
P13	73	97
P14	69	96
P15	70	97
Mean	70.0	96.2

3.9 Discussion

The findings of this study indicate that Smart-ART was technically capable of integrating scheduled medication reminders, medication-event recording, photographic evidence submission, and remote access to adherence information. These functions provide an electronic mechanism for documenting medication-taking behavior beyond retrospective self-report. In the context of ART, adherence refers to the extent to which patients follow the prescribed treatment regimen, including taking medication at the prescribed time and frequency and following relevant treatment instructions (Sahay *et al.,* 2011). In this pilot study, mean ART adherence increased from 70.0% at baseline to 96.2% during the 30-day Smart-ART trial, representing an absolute difference of 26.2 percentage points. Using the ≥95% threshold reported in previous ART adherence research as a reference point, the mean adherence during the Smart-ART period exceeded this level, whereas the baseline mean was substantially lower (Achappa *et al.,* 2013). However, this threshold should be interpreted as a reference from the adherence literature rather than as a universal clinical cutoff. More importantly, the paired Wilcoxon signed-rank test indicated a statistically significant difference between the two measurement periods ($p < 0.001$). Because this study used a single-arm pre–post design without a randomized control group, the observed difference should be interpreted as a preliminary pre–post association rather than definitive evidence of a causal intervention effect.

The adherence measurement used in Smart-ART also differs from conventional adherence assessment based primarily on self-report, pill counts, or the proportion of prescribed doses reported as taken. The Smart-ART measure incorporated the timing of medication intake, defining an adherent medication event as one completed within one hour after the initial medication reminder and supported by photographic evidence. This approach provides additional temporal information about medication-taking behavior. Electronic adherence monitoring has similarly been described as providing time-stamped information that can identify patterns of delayed or missed medication events and support more targeted adherence monitoring (Haberer *et al.,* 2022). Nevertheless, the photographic evidence used in this study was reviewed by HIV care coordinators and should not be considered an independent gold-standard verification of medication ingestion.

The use of a timing-based adherence measure is also consistent with the broader concept of smart medication-management systems, in which medication reminders and monitoring functions are integrated into a single system. Minaam and Abd-ELfattah (2018), for example, described a smart pill-box system designed to provide medication reminders and monitoring functions. In this context, the Smart-ART approach extends conventional dose-based adherence recording by incorporating the temporal relationship between the scheduled medication time and the recorded medication event. The measure therefore provides an additional indicator of medication-taking punctuality, rather than replacing conventional clinical measures of ART adherence.

The technical architecture of Smart-ART also supports the potential use of electronic adherence information for remote monitoring. The system combines a medication box, patient mobile application,

mHealth server, and provider-facing interface, allowing medication-event information to be accessed remotely by HIV care coordinators. This configuration is conceptually consistent with previous work on electronic ART adherence monitoring, in which time-stamped adherence data were used to support adherence counseling and identify periods of delayed or missed medication use (Haberer *et al.,* 2022). In the present study, however, the provider interface should be interpreted primarily as a remote access and monitoring mechanism. The study did not quantify data-transmission latency, intervention response time, or clinical outcomes; therefore, claims regarding real-time intervention effectiveness should not be made.

The design of the patient-facing application incorporated a concise interface and Bahasa Indonesia as the primary interface language, while the physical medication box included batik-themed visual elements. These characteristics were intended to make the prototype contextually appropriate for Indonesian users. Recent mHealth research involving people living with HIV has likewise emphasized the relevance of usability and cultural adaptation in the development of digital interventions (Schnall *et al.,* 2026). However, because the present study did not employ a formal usability scale or assess health literacy, the interface characteristics should be regarded as design features rather than demonstrated evidence of improved usability, reduced cognitive burden, or reduced digital health disparities.

Several technical and methodological limitations should also be considered. First, the prototype depended on Wi-Fi connectivity for communication with the mHealth server, and intermittent connectivity was identified as a practical implementation issue. Previous electronic adherence monitoring research has similarly identified network-related problems as a potential source of technical disruption in remote adherence systems (Haberer *et al.,* 2022). Second, the electrical testing in this study characterized buzzer voltage under the tested conditions but did not constitute a comprehensive assessment of electrical safety or long-term reliability. Third, the pilot involved only 15 participants and was conducted for 30 days at a single urban community health center. These characteristics limit the generalizability of the findings. In addition, no viral load, treatment outcome, or mother-to-child transmission outcome was measured, so the present findings should be interpreted in terms of medication adherence and system feasibility rather than clinical effectiveness.

Overall, Smart-ART demonstrated the technical feasibility of integrating medication reminders, medication-event recording, photographic evidence submission, and remote adherence monitoring in a prototype intended for pregnant women living with HIV. The observed increase in adherence and the statistically significant paired difference provide a basis for further investigation, but they do not establish causality. Future studies should employ larger samples, controlled or randomized designs, longer follow-up periods, formal usability evaluation, quantitative assessment of network and synchronization performance, and clinically relevant outcomes such as viral suppression. Such studies would provide stronger evidence regarding the effectiveness, usability, and implementation feasibility of Smart-ART.

The trial results demonstrated that Smart-ART successfully monitored adherence levels among pregnant women living with HIV undergoing ART. The telemonitoring interface for adherence tracking, managed by HIV care coordinators, and the recorded medication time deviation are presented in Figures 6 and 7, respectively.

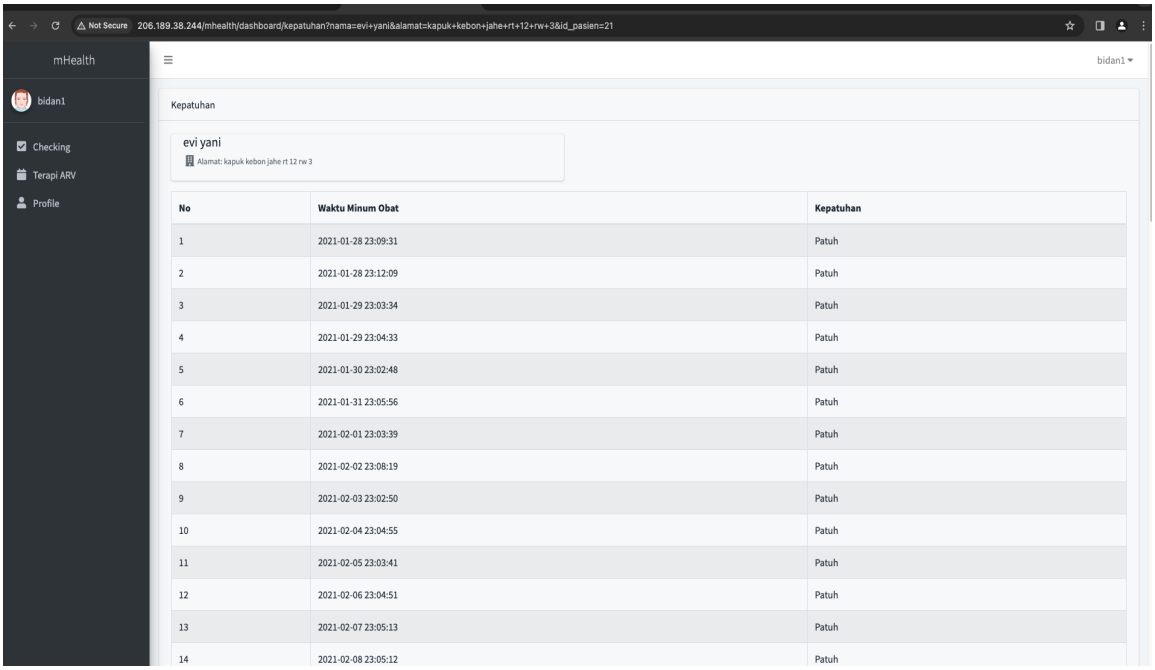


Figure 6. Smart-ART telemonitoring interface for ART adherence monitoring by HIV care coordinators.

Figure 6 shows the telemonitoring interface used by HIV care coordinators to review medication adherence information and recorded medication events. The interface provided remote access to participant adherence records during the pilot period. In addition to adherence status, Smart-ART recorded the time interval between the scheduled medication time and the recorded medication event. Figure 7 presents the average daily time deviation and the corresponding total time deviation over the 30-day observation period.

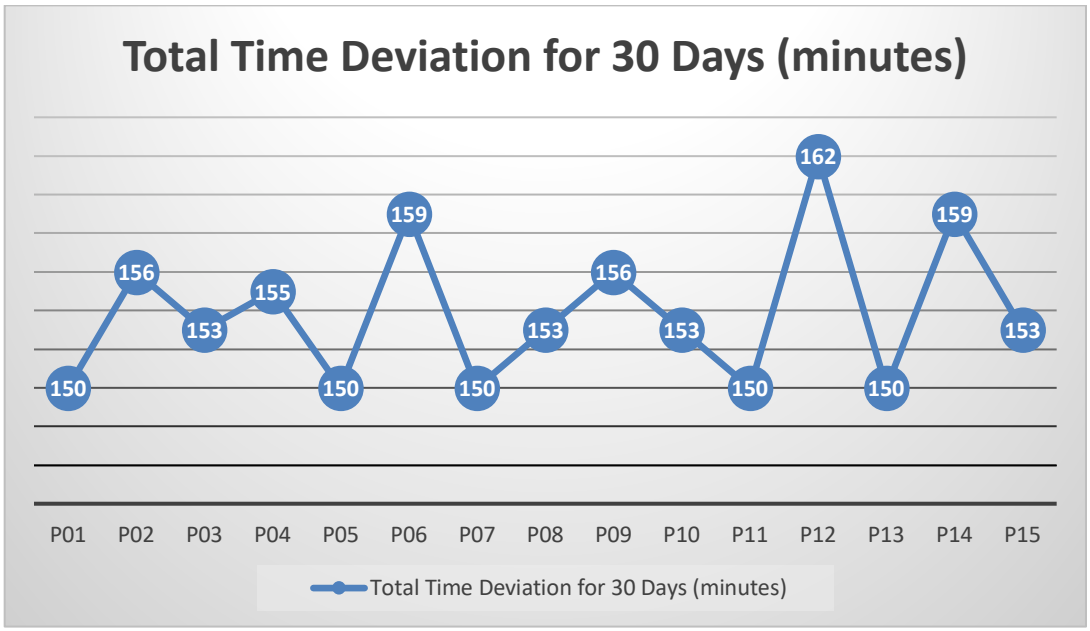


Figure 7. Average daily and total medication time deviation over the 30-day pilot period.

The average time deviation per patient ranged from approximately 5.00 to 5.40 minutes per day. The original analysis summarized the corresponding 30-day values based on the daily averages. The adherence measurement used in Smart-ART incorporated the timing of medication intake, thereby providing temporal information in addition to whether a scheduled dose was recorded as taken. This approach differs from conventional dose-based adherence measures and may provide additional information on medication-taking punctuality (Fedlu *et al.,* 2020; Terefe *et al.,* 2021).

4. Conclusions

This study developed and evaluated Smart-ART, an IoT-enabled medication monitoring system integrating a medication box, patient mobile application, and provider-facing remote monitoring interface. In the 30-day pilot involving 15 pregnant women living with HIV, mean ART adherence increased from 70.0% at baseline to 96.2% during Smart-ART use, representing an absolute difference of 26.2 percentage points. The paired Wilcoxon signed-rank test indicated a statistically significant difference between the two measurement periods ($p < 0.001$). The system also supported scheduled medication reminders, medication-event recording, and photographic submission of medication-intake evidence for review by HIV care coordinators.

These findings demonstrate the technical feasibility of Smart-ART and provide preliminary evidence of improved medication-taking behavior during the pilot period. However, the single-arm pre–post design, small sample size, single healthcare setting, and 30-day follow-up limit causal inference and generalizability. Viral load and other clinical outcomes were not assessed, and intermittent network connectivity remains an implementation consideration. Further controlled studies with larger samples and longer follow-up should evaluate ART adherence using validated measures together with usability, acceptability, implementation feasibility, scalability, cost-effectiveness, and clinical outcomes such as viral suppression.

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6. Conflict of Interest Declaration

The authors declare that there is no conflict of interest regarding the publication of this article. The authors also confirm that this manuscript is original and free from plagiarism.

7. Author Contribution Statement

This journal uses Contributor Roles Taxonomy (CRediT) to recognize individual author contributions, reduce authorship disputes, and facilitate collaboration.

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C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
Va : **Va**lidation
Fo : **Fo**rmal analysis
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R : **R**esources
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Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

8. Generative AI Statement

During the preparation and revision of this manuscript, generative AI tools were used to assist with language refinement, grammatical correction, and editorial improvement of selected manuscript sections. These tools were not used for data collection, statistical analysis, or the generation of research findings. All AI-assisted suggestions were critically reviewed and validated by the authors, who retain full responsibility for the accuracy, originality, and scientific integrity of the final manuscript.

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