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SMART MEDICATION BOX IN HOME MEDICATION MANAGEMENT: PROGRESS, CHALLENGES, AND FUTURE TRENDS

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Abstract: The rapid aging of the global population and the increasing prevalence of chronic diseases have rendered medication management a critical public health challenge. Poor medication adherence among elderly patients leads to compromised therapeutic outcomes, higher complication rates, and increased healthcare costs. Smart medication boxes, which integrate Internet of Things (IoT) technology, embedded systems, and cloud computing, have emerged as promising tools to address these challenges through functions including timed reminders, automated dispensing, medication logging, remote monitoring, and emergency calling. This paper presents a systematic review of technological advancements, product development, and research trends in smart medication boxes. The technical architecture encompassing hardware components and software functions is comprehensively analyzed. Representative products from both international and domestic markets are compared, highlighting differences in functional completeness, cost-effectiveness, and age-friendly design. Key challenges including system reliability, user acceptance, data security, and standardization are identified and discussed. Future development directions incorporating artificial intelligence-assisted decision-making, 5G-enabled edge computing, and policy integration are proposed. This review provides valuable insights for researchers, product developers, and policymakers engaged in smart aging and digital health technologies.
Keywords: Internet of things; Smart medication box; Medication adherence; Aging population; Home medication management; Digital health

1 INTRODUCTION

The global population is experiencing an unprecedented demographic shift toward aging. By the end of 2023, the population aged 65 and above exceeded 210 million, accounting for 15.4% of the total population. The World Health Organization projects that by 2050, the global population aged 60 years and older will approach 2 billion, more than double the figure recorded in 2000. Concurrently, the prevalence of chronic diseases such as diabetes, hypertension, and coronary heart disease continues to rise. These conditions typically require consistent, long-term pharmacological therapy; however, medication adherence among elderly patients remains suboptimal due to factors including cognitive decline, polypharmacy, and insufficient supervision. A systematic review and meta-analysis has demonstrated that digital health tools improve adherence in chronic disease, with adherence rates ranging from 25.3% in institutionalized patients to 97.6% in pharmacist-led programs [1].

Medication non-adherence in older adults is a prevalent and complex issue, attributable to multiple factors including memory impairment, polypharmacy, physical difficulties, personal beliefs, lack of social support, and systemic healthcare barriers [2]. The consequences of poor adherence include diminished therapeutic efficacy, elevated complication risks, and unnecessary hospitalizations with associated medical expenditures. Dose administration aids have been shown to significantly improve medication adherence, with intervention groups achieving median self-reported adherence rates of 95.5% compared to 84.5% in control groups [3]. Furthermore, the sensitivity and specificity of digital technologies for measuring medication adherence have been reported to range from 25% to 99% and 69% to 100%, respectively [4].

Traditional medication boxes provide only basic storage functionality and cannot address practical needs such as scheduled reminders, medication intake tracking, or remote monitoring. With the rapid advancement of IoT, embedded systems, big data analytics, and artificial intelligence technologies, smart medication boxes have gained significant attention in recent years. An updated scoping review identified 114 smart medication dispensing and adherence products (SMAPs), comprising 34 prototypes and 80 commercial solutions, categorized into 15 distinct types [5]. These devices integrate sensors, communication modules, and intelligent algorithms to deliver functions including timed voice reminders, automated dispensing, cloud-based medication record synchronization, and emergency call capabilities, thereby substantially enhancing the intelligence level of home medication management [5].

Several studies have explored smart medication management, including electronic dispensers for reducing dosing errors [6], IoT-enabled pill bottles for real-time adherence feedback, and machine learning approaches for predicting non-adherence patterns [7]. However, existing reviews focus narrowly on device design, clinical outcomes, or user acceptance in isolation, lacking a holistic synthesis of technological architecture, product classification, and deployment challenges. The rapid integration of emerging technologies such as edge computing further renders earlier reviews outdated.

This paper aims to systematically review the current state of technology, product development, existing challenges, and

future directions in the field of smart medication boxes, providing a comprehensive reference for researchers and product developers.

2 TECHNICAL ARCHITECTURE AND FUNCTIONAL CLASSIFICATION

2.1 Hardware Technology

The hardware system of a smart medication box typically comprises a main control chip, sensor modules, communication modules, actuators, and a power management unit. The main control chip serves as the core computing component. Widely adopted solutions include STM32 series microcontrollers and SEP4008 ultra-low-power 32-bit microcontrollers, which offer advantages of low cost, low power consumption, and high stability while meeting fundamental control and data processing requirements. ARM-based embedded processors are employed in certain high-end products to support more sophisticated algorithms and graphical user interfaces.

Sensor modules primarily consist of environmental sensors (e.g., temperature and humidity sensors), medication compartment status sensors (e.g., pressure sensors and photoelectric sensors), and acoustic localization or infrared sensors. These sensors enable real-time monitoring of medication storage conditions and usage patterns, thereby ensuring pharmaceutical quality. Hardware features including battery life, medication storage capacity, availability and variety of alerts, locking features, and supplementary technologies required for product operation have been identified in the updated scoping review. The importance of appropriate microcontroller selection and sensor integration has been emphasized in a review of smart medication box features.

Power management is designed with consideration for home-based elderly care scenarios. Smart medication boxes typically incorporate low-power design strategies and rechargeable batteries to maintain normal operation during power outages. NB-IoT technology is utilized by certain products, such as Pillsure Pocket, to provide wide coverage, low power consumption, autonomous operation, and remote programmability [8]. NB-IoT-based solutions have been demonstrated to address battery life challenges effectively [8].

2.2 Communication Technology and Software Functions

The software system of a smart medication box is generally built upon an embedded operating system such as FreeRTOS, µC/OS, or Linux, with Android being used for more advanced feature requirements. The primary software functions include the following modules.

Medication reminders and schedule management: Users or family members can configure the timing, dosage, and frequency of each medication through a mobile application or the device interface. At the designated time, the medication box issues reminders via voice prompts, buzzer alerts, or flashing indicators. Certain systems support multiple reminder cycles until the medication-taking action is acknowledged by the user.

Cloud synchronization and medication recording: The system records each medication-taking event, including the time and type of medication. This information is transmitted to a cloud server via WiFi or 4G/5G networks, enabling healthcare providers and family members to remotely review the patient's medication status and promptly identify missed or incorrect doses. According to the scoping review, data collection methods include sensors that track product usage and data-synchronization capabilities with cloud storage, with users able to access data through web-based portals or mobile applications.

Human-computer interaction interface: Smart medication boxes typically feature liquid crystal displays with large fonts, high contrast ratios, and voice interaction capabilities, designed with consideration for elderly users' behavioral patterns. A pilot study evaluating smart pillbox acceptability among primary care patients reported that 70.6% of participants expressed willingness to use the device. User interface design considerations for medication dispensers have been systematically examined from a human-centered perspective [9].

Emergency call functionality: Most smart medication boxes are equipped with an SOS one-key emergency call button. Upon prolonged activation, the device automatically dials the emergency number or a preset contact while transmitting an assistance request and real-time location information to family members' mobile devices.

2.3 Essential Functions

Based on current research and product analysis, the core functions of smart medication boxes can be categorized into six major types, as summarized in Table 1.

Table 1 Essential Functions of Smart Medication Boxes

Function Category	Description	Technical Support
Timed Reminder	Issues medication-taking reminders at preset times	Real-time clock system; voice broadcast
Automatic Dispensing	Automatically dispenses the corresponding medication according to instructions	Motor control; compartment partitioning
Medication Recording	Records the time and type of each medication-taking event	Sensor detection; data storage

Function Category	Description	Technical Support
Remote Monitoring	Enables family members and physicians to remotely view medication status	Cloud server; application push notifications
Emergency Call	Transmits help requests via one-button activation	Communication module; GPS positioning
Drug Management	Provides medication expiration reminders and classification storage	Database management; barcode recognition

3 COMPARATIVE ANALYSIS OF DOMESTIC AND INTERNATIONAL PRODUCTS

3.1 International Products

Numerous smart medication dispensing and adherence products have been developed for the global market. An updated scoping review identified 114 SMAPs, of which 68% (54/80) of marketed products were available for consumer purchase; 26% (14/54) were available globally, and 78% (42/54) were available in North America. Products such as Hero and PillDrill have been introduced to markets in North America and Europe. Hero is an automated pill dispenser capable of storing up to ten different medications and dispensing a single dose at a predetermined time. PillDrill scans barcodes to record medication usage and generates logs of mood and symptoms. Additionally, the Pillsure Pocket smart pill dispenser enables autonomous operation through NB-IoT technology, allowing remote configuration via a smartphone application while maintaining patient mobility outside the home environment. A multi-country study on tuberculosis care demonstrated the feasibility and acceptability of smart pillboxes, with favorable patient acceptance observed across diverse settings [10]. Although these products are functionally comprehensive, they generally entail high costs, complex operating procedures, and insufficient consideration of the cognitive capabilities of elderly users.

3.2 Domestic Products and Research

Although the domestic smart medication box market was established somewhat later, it has experienced rapid growth. Domestic companies have developed products featuring medication logging and timed reminder functions at relatively affordable price points. However, capabilities such as environmental monitoring and automated dispensing still require further refinement. National-level research projects on accessible human factors design of home smart medication boxes for the elderly have proposed several age-friendly design principles based on systematic examination of the human-computer interaction interface and operational workflow. More recent smart medication boxes offer extended service life, reduced energy consumption, and supplementary features including cloud data sharing and online physician communication.

Research employing an extended UTAUT model to investigate older adults' adoption of smart product-service systems for medication management revealed that performance expectancy, effort expectancy, social influence, self-efficacy, health awareness, and medical service satisfaction significantly influence behavioral intention [11]. This finding underscores the importance of understanding local consumer preferences for successful product adoption in the domestic market. In pursuit of reduced power consumption and broader coverage, several research teams have also explored smart medication box monitoring systems based on NB-IoT technology, which are suitable for deployment in remote-area home-based elderly care scenarios.

3.3 Comparative Summary

Both domestic and international smart medication box products exhibit respective strengths and weaknesses in terms of research depth and technological advancement. International products demonstrate greater maturity in commercialization and functional completeness but are characterized by higher costs and insufficient localization. Domestic products offer advantages in cost-effectiveness, policy responsiveness, and age-friendly design, yet require further development in core technologies including low-power communication and high-precision sensors, as well as in brand influence.

4 CURRENT CHALLENGES AND ISSUES

Despite significant progress in smart medication box technology, numerous obstacles remain in practical promotion and deployment.

4.1 Technical Challenges

System stability and failure risks: Smart medication boxes incorporate multiple electronic components and mechanical actuators. During extended operation, problems including sensor malfunction, motor jamming, and communication disruption may directly compromise medication safety.

Compatibility issues: Various healthcare institutions employ different medication databases and electronic medical record systems. Smart medication boxes may encounter inconsistent interfaces and incompatible data formats when integrating with these systems. System integration challenges remain a significant barrier according to a human-centered systematic review.

Battery life and power consumption: Medication boxes with autonomous following capabilities significantly increase power consumption through mobile chassis operation and continuous positioning functions. Balancing battery life with functional completeness remains a technical challenge. Battery life is identified as one of the most critical hardware characteristics of SMAPs in the updated scoping review. Products leveraging NB-IoT technology, such as Pillsure Pocket, address both connectivity and battery longevity challenges.

4.2 Market Adoption and User Acceptance

Price considerations: Fully functional smart medication boxes currently exceed 1,000 RMB in price, presenting a substantial financial burden for elderly individuals with limited income. The tension between cost containment and functional completeness restricts product market penetration. The scoping review notes that while some SMAPs are offered to end users at fixed prices or free of charge, the cost of other products varies depending on availability, shipping fees, and subscription charges.

Digital divide among the elderly: Despite the emphasis on age-friendly design in product development, a substantial proportion of elderly individuals continue to exhibit apprehension toward smart devices, necessitating extended learning and adaptation periods. Some elderly users experience difficulty performing daily operations and initial setup independently due to diminished vision, hearing, or cognitive abilities. Digital literacy and user training have been identified as implementation challenges in a scoping review of mHealth interventions for medication management [12]. Technical support and user training are essential for the successful implementation of smart pillboxes, as demonstrated in a multi-country study.

Trust concerns: Given the safety-critical nature of medication management devices, users maintain exceptionally high standards for reliability. A single missed or misdirected reminder may erode user confidence and precipitate reversion to conventional methods. The efficacy of digital adherence solutions varies considerably, and inaccurate measurements may undermine user trust, according to a systematic review.

4.3 Privacy and Data Security

Smart medication boxes collect and transmit sensitive personal information, including medication records, health data, and location information. According to the updated scoping review, while some SMAPs provide data security assurance through secure log-in mechanisms (e.g., facial recognition or personal identification numbers), others deliver data through registered email addresses. Vulnerabilities persist in data transmission encryption, cloud storage security, and external access rights management. A data breach could precipitate legal complications and privacy concerns.

4.4 Standardization and Policy Concerns

As emerging products, smart medication boxes currently lack inclusion in the national medical device classification catalog, and no unified product standards or quality control mechanisms have been established. Products from different manufacturers vary substantially in terms of functional definitions, safety performance, and data interfaces, which impedes the healthy development of the industry. Additionally, the uncertainty regarding whether smart medication boxes can be incorporated into medical insurance payment systems or qualify for elderly care subsidies further constrains their promotion. System-level reforms and financial support mechanisms may further facilitate medication adherence, while digital health solutions require attention to literacy, accessibility, and integration challenges for successful deployment, according to a systematic review of multilevel interventions [12].

5 FUTURE DEVELOPMENT TRENDS AND STRATEGIES

5.1 Technological Development Trends

AI-assisted decision-making: Future smart medication boxes are expected to evolve beyond passive reminder devices into active health management platforms that provide personalized medication adjustment recommendations based on users' health data (e.g., blood pressure and blood glucose monitoring results) and alert physicians to abnormal conditions. A systematic review and meta-analysis demonstrated that digital technologies improve medication adherence in chronic disease settings and that machine learning models can accurately predict non-adherence, with AUC values reaching up to 0.935. The potential of AI-driven interventions has also been emphasized in a scoping review of mHealth technologies [12].

5G and edge computing: The high bandwidth and low latency characteristics of 5G networks will enable more seamless real-time communication between medication boxes and medical service platforms. Edge computing can reduce cloud dependency by processing certain data locally, thereby enhancing data security and system response times. 5G technology provides massive IoT connectivity, ultra-reliable low-latency communication, and substantially higher data transfer speeds.

Multimodal interaction: To achieve genuinely barrier-free design, future smart medication boxes will incorporate multiple input modalities—including voice, touch, gesture, and potentially eye tracking—to accommodate elderly users with diverse cognitive abilities and physical conditions. The importance of user-centered design for varied demographic groups has been demonstrated in a pilot study on smart pillbox acceptability and highlighted in a scoping review of mHealth

technologies [12].

5.2 Expansion of Application Scenarios

Smart medication boxes are expected to be deployed across diverse settings including households, residential senior care facilities, and rural health clinics. By integrating with primary healthcare service systems, the smart medication box can function as a terminal node for chronic disease management, connecting medication information with services provided by contracted family physicians. Research on tuberculosis treatment has demonstrated the feasibility of smart pillboxes across varied healthcare environments, including remote rural locations and urban clinics.

5.3 Policy Recommendations

Integration into elderly care service systems: It is recommended that smart medication boxes be incorporated into the subsidy catalog for age-friendly home modifications under residential elderly care programs, providing purchase subsidies to eligible low-income elderly individuals. Socioeconomic barriers, including medication costs, contribute to non-adherence but may be mitigated through subsidies, as indicated by a systematic review. Medical service satisfaction significantly influences adoption intention among older adults, according to an extended UTAUT study, suggesting the importance of policy support and service integration.
Establishment of industry standards: Relevant industry authorities are advised to expeditiously develop technical standards and safety specifications for smart medication boxes, articulating product classification, performance indicators, and data security requirements to foster healthy competition within the sector.
Exploration of medical insurance payment mechanisms: For patients with chronic diseases requiring long-term polypharmacy, smart medication boxes can substantially reduce hospitalizations and emergency department visits resulting from medication errors, demonstrating significant health economic benefits. A systematic review of dose administration aids showed that effective interventions improve adherence and reduce medication errors. Furthermore, a systematic review and meta-analysis of digital interventions reported a 25–59% improvement in adherence and reductions in cardiovascular events. The successful deployment of smart pillboxes in tuberculosis programs across multiple countries provides a model for integrating such devices into public health insurance frameworks. Pilot implementation of smart medication box payment through medical insurance personal accounts is recommended in eligible regions.

6 CONCLUSION

The smart medication box represents a convergence of IoT technology and medical health requirements, carrying substantial practical significance for addressing population aging and improving medication adherence among patients with chronic diseases. This paper has provided a systematic review of the smart medication box field across four dimensions: technological architecture, product status, current challenges, and development trends.
The findings indicate that smart medication boxes have achieved mature hardware solutions based on low-power microcontrollers with multi-sensor and communication module integration, and have realized core functions including medication logging, timed reminders, and remote monitoring at the software level. While domestic products offer certain advantages in cost-effectiveness and age-friendly design compared to international alternatives, gaps remain in core technologies and brand influence. The development of smart medication boxes currently faces multiple challenges encompassing technical reliability, user acceptance, data security, and standardization. With the integration of emerging technologies such as artificial intelligence and 5G connectivity, alongside the improvement of relevant policies, smart medication boxes are anticipated to assume an increasingly critical role in home medication management and smart elderly care.
To fully realize this potential, future research should prioritize the following directions: large-scale randomized controlled trials assessing long-term efficacy and cost-effectiveness across diverse patient populations and healthcare settings; AI-driven personalized medication management that integrates multi-source health data—such as blood pressure, blood glucose, and physical activity levels—for intelligent and adaptive scheduling; seamless integration with telemedicine platforms and electronic health record systems to achieve comprehensive healthcare data interoperability; user-centered design research targeting elderly users with varying levels of digital literacy and cognitive capacity to develop more accessible and inclusive products; health economic evaluations and policy studies to establish sustainable reimbursement models enabling deployment within public health systems; and longitudinal studies tracking medication adherence outcomes and health-related quality of life to provide robust evidence for the sustained benefits of smart medication box interventions.

COMPETING INTERESTS

The authors have no relevant financial or non-financial interests to disclose.

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