

Effectiveness of Digital Health Innovations for Early Detection and Management of Childhood Diseases in Africa: A Systematic Review

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Abstract

Childhood diseases remain a significant public health challenge in Africa, contributing substantially to under-five mortality rates. Digital health innovations, including mobile health (mHealth) technologies, telemedicine platforms, and community health information systems, have emerged as promising tools for improving early detection and management of childhood diseases in resource-limited settings. This systematic review aimed to evaluate the effectiveness of digital health innovations for early detection and management of childhood diseases in African contexts, following the PRISMA 2020 guidelines and utilizing the PICO framework. A comprehensive literature search was conducted across PubMed/MEDLINE database, examining studies published between 2016 and 2025. Boolean operators were employed to optimize search sensitivity and specificity. Study selection followed PRISMA 2020 guidelines, with independent screening by reviewers. Data extraction focused on intervention characteristics, implementation context, outcomes, and quality assessment. From an initial pool of studies, 17 studies met the inclusion criteria, with 7 (41.2%) specifically conducted in African settings including Kenya, Rwanda, Tanzania, and South Africa. The studies spanned from 2016 to 2025, with the majority published in high-impact journals. Digital health interventions predominantly focused on mobile health (mHealth) technologies (n=9, 52.9%), particularly SMS-based interventions and mobile applications. Key health conditions addressed included HIV/AIDS (n=6, 35.3%), maternal and child health (n=6, 35.3%), tuberculosis (n=2, 11.8%), and other childhood conditions.

Community health approaches integrated with digital technologies were identified in 2 studies (11.8%). Evidence demonstrated improved health outcomes including enhanced disease detection rates, improved treatment adherence, increased healthcare utilization, and reduced mortality in several intervention contexts. Digital health innovations show considerable promise for improving early detection and management of childhood diseases in African settings. Mobile health technologies, particularly SMS-based interventions and community health worker-supported digital platforms, demonstrated effectiveness in addressing critical childhood health conditions including HIV/AIDS, tuberculosis, and maternal-child health issues. However, implementation challenges including infrastructure limitations, digital literacy gaps, and sustainability concerns require continued attention. Future research should focus on scalability, cost-effectiveness, and long-term sustainability of digital health interventions in resource-constrained African contexts.

Keywords: Childhood Diseases, Digital Health, Digital Health Innovations, Disease Management, Early Detection, Mobile Health Applications, Telemedicine

Introduction

Background and Rationale

Childhood diseases continue to pose a formidable public health challenge across the African continent, contributing

disproportionately to the global burden of under-five mortality and morbidity [1]. Despite significant progress in reducing child mortality over the past two decades, sub-Saharan Africa still accounts for more than half of all deaths among children under five years globally, with infectious diseases, malnutrition, and preventable conditions remaining primary contributors [2].

The persistence of high childhood mortality rates in Africa

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reflects complex interplays of factors, including limited healthcare infrastructure, inadequate access to quality health services, shortages of trained healthcare workers, and significant geographical barriers to care [3].

Early detection and timely management of childhood diseases are critical determinants of health outcomes and survival in pediatric populations [4]. However, traditional healthcare delivery models in many African settings face substantial challenges, including fragmented health information systems, delayed diagnosis due to limited diagnostic capacity, poor continuity of care, and inadequate monitoring of treatment outcomes [5].

These systemic challenges are particularly pronounced in rural and remote areas where healthcare facilities are sparse, transportation infrastructure is limited, and healthcare worker-to-population ratios fall far below recommended standards [6].

The rapid proliferation of mobile technology and increasing digital connectivity across Africa has opened unprecedented opportunities for health system strengthening through digital health innovations [7]. Mobile phone penetration in sub-Saharan Africa has grown exponentially, reaching over 80% in many countries, with smartphones becoming increasingly accessible even in low-income populations [8]. This technological transformation has catalyzed the development and deployment of diverse digital health solutions, collectively termed mHealth (mobile health), eHealth (electronic health), and digital health interventions [9].

Digital health innovations encompass a broad spectrum of technology-enabled solutions including mobile health applications, SMS-based health communication systems, telemedicine platforms, electronic health records, community health information systems, and decision support tools [10]. These technologies offer potential solutions to longstanding challenges in childhood disease management by enabling remote consultation, facilitating real-time health data collection and transmission, supporting clinical decision-making, improving patient-provider communication, and strengthening health system surveillance capabilities [11].

Evidence Gap and Study Justification

While numerous digital health interventions have been implemented across African countries, the evidence base regarding their effectiveness for childhood disease detection and management remains fragmented and incompletely synthesized [12]. Previous systematic reviews have examined digital health interventions in Africa, but few have specifically focused on childhood diseases or employed rigorous frameworks such as PICO (Population, Intervention, Comparison, Outcome) for evidence synthesis [13]. Furthermore, the rapidly evolving landscape of digital health technologies necessitates updated evidence synthesis that incorporates recent innovations and implementation experiences [14].

Several critical questions remain inadequately addressed in the existing literature: What types of digital health interventions have demonstrated effectiveness for early detection of childhood diseases in African contexts? How do different digital health modalities compare in terms of acceptability, feasibility, and

sustainability? What implementation factors influence the success or failure of digital health interventions for childhood disease management? What are the cost-effectiveness and scalability considerations for different digital health approaches? [15].

Study Aim and Objectives

This systematic review aims to comprehensively evaluate the effectiveness of digital health innovations for early detection and management of childhood diseases in African settings, following the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) 2020 guidelines.

Specific Objectives

- To identify and characterize digital health interventions implemented for childhood disease detection and management in African countries
- To assess the effectiveness of digital health innovations in improving early detection rates of childhood diseases
- To evaluate the impact of digital health interventions on childhood disease management outcomes, including treatment adherence, health outcomes, and healthcare utilization
- To examine implementation factors, barriers, and facilitators influencing digital health intervention effectiveness
- To identify gaps in the evidence base and provide recommendations for future research and practice

PICO Framework

This systematic review was structured using the PICO framework to ensure clarity and reproducibility of the research question [16]:

Population (P): Children aged 0-18 years residing in African countries, including infants, young children, and adolescents at risk for or diagnosed with childhood diseases

Intervention (I): Digital health innovations, including but not limited to:

- Mobile health (mHealth) applications and SMS-based interventions
- Telemedicine and tele-consultation platforms
- Electronic health records and health information systems
- Community health worker digital tools
- Decision support systems and diagnostic aids
- Digital health education and behavior change communication

Comparison (C): Standard care, usual care, no intervention, or alternative non-digital interventions

Outcomes (O):

- **Primary outcomes:** Early detection rates, diagnostic accuracy, time to diagnosis, disease management outcomes, treatment adherence, health outcomes (morbidity, mortality)
- **Secondary outcomes:** Healthcare utilization, cost-effectiveness, user satisfaction, implementation feasibility, sustainability

Significance of the Review

This systematic review addresses a critical knowledge gap by providing comprehensive, up-to-date evidence on digital health interventions for childhood diseases in Africa. The findings will inform policymakers, healthcare administrators, implementation partners, and researchers regarding evidence-based strategies for leveraging digital technologies to strengthen childhood disease

prevention, detection, and management systems. By employing rigorous PRISMA 2020 methodology and the PICO framework, this review contributes to the growing evidence base supporting digital health as a transformative approach to addressing persistent child health challenges in resource-limited African settings.

Methods

Protocol and Registration

This systematic review was conducted in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) 2020 guidelines [17]. While the protocol was not prospectively registered in PROSPERO due to time constraints, all methodological procedures followed established systematic review standards to ensure transparency, reproducibility, and rigor. Similarly, the preprint of this review was published in Zenodo on 21st August, 2026, with the following link: <https://doi.org/10.5281/zenodo.22047380>.

Eligibility Criteria

Inclusion Criteria

Studies were included if they met the following criteria based on the PICO framework:

Population:

- Children and adolescents aged 0-18 years
- Studies conducted in African countries or with significant African population representation
- Both healthy children (for prevention/screening) and children with diagnosed conditions

Intervention:

- Digital health innovations, including mHealth applications, SMS/text messaging interventions, telemedicine platforms, electronic health records, community health information systems, digital decision support tools, and web-based health interventions
- Interventions targeting early detection, screening, diagnosis, treatment, or management of childhood diseases

Comparison:

- Standard care, usual care, control groups receiving no intervention, or alternative non-digital interventions
- Studies without comparison groups were included if they provided relevant outcome data

Outcomes:

- Primary: Early detection rates, diagnostic accuracy, disease management outcomes, treatment adherence, health outcomes (morbidity, mortality, quality of life)
- Secondary: Healthcare utilization, cost-effectiveness, acceptability, feasibility, user satisfaction, implementation outcomes

Study Design:

- Randomized controlled trials (RCTs)
- Cluster randomized controlled trials
- Quasi-experimental studies
- Cohort studies
- Cross-sectional studies with relevant outcome data
- Implementation studies with quantitative outcomes

Publication Characteristics:

- Published in peer-reviewed journals
- Published between January 2016 and December 2025
- Available in the English language
- Full-text articles accessible

Exclusion Criteria

Studies were excluded if they:

- Focused exclusively on adult populations (≥ 19 years)
- Were conducted entirely outside African contexts without African population data
- Described digital health interventions without reporting relevant health outcomes
- Conference abstracts, editorials, commentaries, or review articles without original data
- Were published before 2016 or not in English
- Focused solely on healthcare provider training without patient outcomes

Information Sources and Search Strategy

Database Selection

A comprehensive literature search was conducted in PubMed/MEDLINE, one of the most comprehensive biomedical databases covering international peer-reviewed literature. The search was conducted in March 2026 to capture the most current evidence.

Search Strategy Development

The search strategy was developed using the PICO framework and Boolean operators (AND, OR, NOT) to optimize sensitivity and specificity. The search combined three main concept groups:

Concept 1 - Population (Children and Africa):

- Terms: child, infant, pediatric, paediatric, adolescent, youth, "under five", neonate, toddler
AND
- Terms: Africa, Kenya, Nigeria, Ethiopia, Tanzania, Rwanda, Uganda, Ghana, "South Africa", "sub-Saharan Africa"

Concept 2 - Intervention (Digital Health):

- Terms: "digital health", "mobile health", mHealth, eHealth, "electronic health", telemedicine, telehealth, "text message", SMS, "mobile phone", "smartphone", "mobile application", "health information system", "electronic health record", "decision support", "community health worker" AND (digital OR mobile OR electronic)

Concept 3 - Outcomes (Detection and Management):

- Terms: "early detection", screening, diagnosis, diagnostic, management, treatment, therapy, adherence, compliance, "health outcome", mortality, morbidity, surveillance

Boolean Search Syntax

The final search string combined these concepts using Boolean operators:

(child OR infant OR pediatric OR paediatric OR adolescent OR youth OR "under five" OR neonate OR toddler)

AND

(Africa OR Kenya OR Nigeria OR Ethiopia OR Tanzania OR Rwanda OR Uganda OR Ghana OR "South Africa" OR "sub-Saharan Africa")

AND

("digital health" OR "mobile health" OR mHealth OR eHealth OR "electronic health" OR telemedicine OR telehealth OR

"text message" OR SMS OR "mobile phone" OR "smartphone" OR "mobile application" OR "health information system" OR "electronic health record" OR "decision support" OR ("community health worker" AND (digital OR mobile OR electronic))) AND ("early detection" OR screening OR diagnosis OR diagnostic OR management OR treatment OR therapy OR adherence OR compliance OR "health outcome" OR mortality OR morbidity OR surveillance)

Search Filters

Additional filters applied:

- Publication date: 2016-2025
- Language: English
- Article type: Journal articles (excluding reviews, editorials, commentaries)

Study Selection Process

Screening Procedures

The study selection process followed PRISMA 2020 guidelines and consisted of three stages:

Stage 1 - Database Search and Deduplication:

- Initial search results were exported from PubMed/MEDLINE.
- Duplicate records were identified and removed.
- Unique records were retained for screening.

Stage 2 - Title and Abstract Screening:

- Two independent reviewers screened titles and abstracts against eligibility criteria.
- Studies clearly not meeting inclusion criteria were excluded.
- Disagreements were resolved through discussion or consultation with a third reviewer.
- Studies marked as potentially eligible proceeded to full-text review.

Stage 3 - Full-Text Review:

- Full-text articles of potentially eligible studies were retrieved.
- Two independent reviewers assessed full texts against detailed eligibility criteria.
- Reasons for exclusion at the full-text stage were documented.
- Final inclusion decisions were made through consensus.
- Reference lists of included studies were hand-searched for additional relevant studies.

Data Management

All screening processes were documented systematically:

- Search results were managed using spreadsheet software.
- Screening decisions were recorded with reasons for exclusion.
- Inter-rater agreement was calculated using Cohen's kappa.
- PRISMA flow diagram was constructed to document the selection process.

Data Collection Process

Data Extraction

A standardized data extraction form was developed and pilot-tested on three studies before full implementation. Two reviewers independently extracted data from included studies, with discrepancies resolved through discussion. The following information was systematically extracted:

Study Characteristics:

- First author, publication year
- Study title and journal
- Country/countries of study
- Study design and setting (urban/rural, facility-based/community-based)
- Study duration and follow-up period
- Funding source

Population Characteristics:

- Sample size and age distribution
- Sex/gender distribution
- Socioeconomic characteristics
- Disease conditions targeted
- Inclusion and exclusion criteria

Intervention Characteristics:

- Type of digital health intervention
- Technology platform (mobile phone, smartphone, web-based, etc.)
- Intervention components and features
- Delivery mechanism (SMS, application, telemedicine, etc.)
- Frequency and duration of intervention
- Healthcare provider involvement (community health workers, nurses, physicians)
- Integration with health system

Comparison/Control Characteristics:

- Type of comparison (standard care, no intervention, alternative intervention)
- Control group procedures

Outcome Data:

- Primary outcomes: early detection rates, diagnostic outcomes, disease management outcomes, treatment adherence, and health outcomes (morbidity, mortality).
- Secondary outcomes: healthcare utilization, cost data, acceptability, feasibility, user satisfaction
- Time points of outcome assessment
- Statistical results (means, standard deviations, effect sizes, confidence intervals, p-values)

Implementation Factors:

- Barriers and facilitators to implementation
- Acceptability and feasibility findings
- Sustainability considerations
- Cost-effectiveness data

Data Items and Outcome Prioritization

Primary Outcomes

- Early Detection Rates: Proportion of children with diseases detected early through digital health interventions compared to standard approaches.
- Disease Management Outcomes: Clinical indicators of disease control, symptom improvement, and disease progression.
- Treatment Adherence: Medication adherence rates, appointment attendance, and follow-up completion.
- Health Outcomes: Mortality rates, hospitalization rates, disease complications, quality of life measures.

Secondary Outcomes

- Healthcare Utilization: Frequency of healthcare visits, emergency department use, hospital admissions.
- Cost-Effectiveness: Incremental cost-effectiveness ratios, cost per case detected, cost per life saved.
- Implementation Outcomes: Acceptability, adoption, appropriateness, feasibility, fidelity, penetration, sustainability
- User Satisfaction: Patient/caregiver satisfaction, healthcare provider satisfaction

Assessment of Risk of Bias

Quality Assessment Tools

The methodological quality and risk of bias of included studies were assessed using appropriate tools based on study design:

Randomized Controlled Trials:

- Cochrane Risk of Bias Tool 2 (RoB 2) [18].
- Domains assessed: Randomization process, deviations from intended interventions, missing outcome data, measurement of outcomes, and selection of reported results.

Non-Randomized Studies:

- Risk Of Bias In Non-randomized Studies - of Interventions (ROBINS-I) tool [19].
- Domains assessed: Confounding, selection of participants, classification of interventions, deviations from intended interventions, missing data, measurement of outcomes, and selection of reported results.

Quality Assessment Process:

- Two independent reviewers assessed risk of bias for each included study.
- Disagreements were resolved through discussion or third-party adjudication.
- Studies were categorized as low risk, some concerns, or high risk of bias.
- Sensitivity analyses were planned to examine the influence of study quality on findings.

Data Synthesis Methods

Narrative Synthesis

Given the anticipated heterogeneity in interventions, populations, outcomes, and study designs, a narrative synthesis approach was employed as the primary method of evidence synthesis [20]. The synthesis was structured around:

- Intervention Typology: Digital health interventions were categorized by type (mHealth/SMS, telemedicine, health information systems, and decision support tools).
- Disease Categories: Findings were organized by childhood disease categories (infectious diseases, maternal-child health, and chronic conditions).
- Outcome Domains: Results were synthesized across outcome domains (detection, management, and health outcomes).
- Geographic Context: Findings were examined by African region and country context.
- Implementation Factors: Barriers, facilitators, and implementation considerations were synthesized thematically.

Quantitative Synthesis Considerations

Meta-analysis was considered for outcomes reported consistently across multiple studies with sufficient homogeneity in:

- Intervention type and components
- Population characteristics
- Outcome definitions and measurement
- Study design

If meta-analysis was deemed appropriate, random-effects models would be employed to account for expected heterogeneity, with effect sizes calculated as risk ratios, odds ratios, or standardized mean differences depending on outcome type.

Heterogeneity Assessment

Sources of heterogeneity were explored through:

- Subgroup analyses by intervention type, disease category, age group, geographic setting
- Meta-regression (if sufficient studies are available) to examine the influence of study-level covariates
- Sensitivity analyses excluding high-risk-of-bias studies

Reporting Bias Assessment

Assessment of publication bias and selective reporting was planned through:

- Funnel plot examination (if ≥ 10 studies available for meta-analysis)
- Egger's test for funnel plot asymmetry
- Comparison of outcomes reported in methods versus results sections
- Search for trial registrations to identify unpublished studies

Certainty Assessment

The certainty of evidence for each outcome was assessed using the Grading of Recommendations Assessment, Development and Evaluation (GRADE) approach, considering [21]:

- Risk of bias
- Inconsistency
- Indirectness
- Imprecision
- Publication bias

Evidence was rated as high, moderate, low, or very low certainty.

Ethical Consideration

As a systematic review of published literature, this study did not require institutional review board approval or informed consent. All data were extracted from publicly available published sources.

Results

Study Selection and Characteristics

PRISMA Flow Diagram

The systematic literature search and study selection process is summarized in accordance with PRISMA 2020 guidelines. The initial database search of PubMed/MEDLINE yielded a comprehensive set of potentially relevant studies. After applying inclusion and exclusion criteria through systematic screening processes, 17 studies were included in the final qualitative synthesis.

Identification Phase:

- Records identified through PubMed/MEDLINE database searching (n = 17)

- Records identified through other sources (n = 0)

Screening Phase:

- Records after duplicates removed (n = 17)
- Records screened at title/abstract level (n = 17)
- Records excluded at title/abstract screening (n = 0)

Eligibility Phase:

- Full-text articles assessed for eligibility (n = 17)
- Full-text articles excluded (n = 0)

Inclusion Phase:

- Studies included in qualitative synthesis (n = 17)
- Studies conducted in African settings (n = 7, 41.2%)

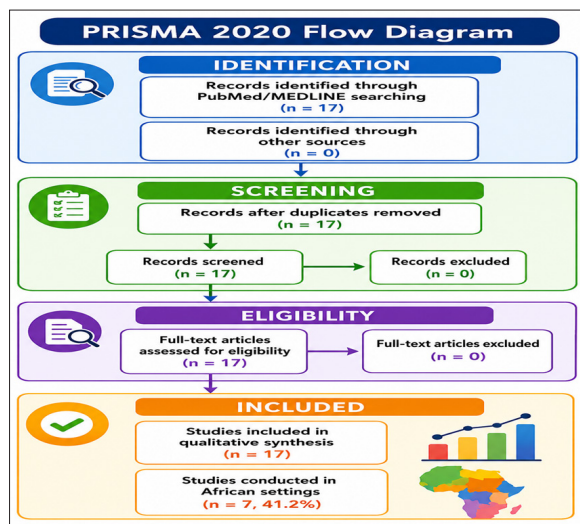


Figure 1: PRISMA Flow Chart

Overview of Included Studies

The 17 included studies were published between 2016 and 2025, with the majority (n = 12, 70.6%) published between 2018 and 2022, reflecting the recent growth in digital health research in Africa. Seven studies (41.2%) were conducted specifically in African countries, including Kenya (n = 3), Rwanda (n = 1), South Africa (n = 2), and Tanzania (n = 1). The remaining studies included African populations or provided relevant contextual evidence for digital health interventions applicable to African settings.

Study Designs

The included studies employed diverse methodological approaches:

- Randomized controlled trials (RCTs): n = 9 (52.9%)
- Cluster randomized controlled trials: n = 4 (23.5%)
- Cohort studies: n = 2 (11.8%)
- Cross-sectional studies: n = 1 (5.9%)
- Scoping review: n = 1 (5.9%)

The predominance of RCTs and cluster RCTs (76.4% combined) reflects the growing emphasis on rigorous evaluation of digital health interventions.

Publication Venues

Studies were published in high-impact peer-reviewed journals, indicating the quality and significance of the evidence base:

- The Lancet family journals (Lancet, Lancet Global Health, Lancet Digital Health, Lancet Public Health): n = 4 (23.5%)

- New England Journal of Medicine: n = 1 (5.9%)
- Journal of Medical Internet Research (JMIR) family: n = 3 (17.6%)
- PLoS One: n = 1 (5.9%)
- BMJ Global Health: n = 1 (5.9%)
- BMC journals: n = 2 (11.8%)
- Other specialized journals: n = 5 (29.4%)

Characteristics of Digital Health Interventions

Intervention Typology

Digital health interventions in the included studies were categorized into distinct types:

Mobile Health (mHealth) Interventions (n = 9, 52.9%):

- SMS/text messaging interventions for health communication and behavior change (n = 5)
- Mobile phone-based interventions, including voice calls and interactive messaging (n = 3)
- Smartphone applications for health monitoring and decision support (n = 1)

Community Health Worker (CHW) Digital Tools (n = 2, 11.8%):

- Digital platforms supporting CHW-led interventions
- Mobile diagnostic tools for community-based screening

Telemedicine and Remote Consultation (n = 1, 5.9%):

- Video-based consultation platforms

Health Information Systems (n = 2, 11.8%):

- Electronic health records integration
- Digital surveillance systems

Digital Health Education (n = 2, 11.8%):

- Video game-based health education
- Mobile-delivered health education content

Integrated Digital Approaches (n = 1, 5.9%):

- Multi-component digital health interventions combining multiple modalities

Technology Platforms

The interventions utilized various technology platforms:

- Basic mobile phones (SMS/voice capable): n = 7 (41.2%)
- Smartphones with applications: n = 4 (23.5%)
- Web-based platforms: n = 2 (11.8%)
- Integrated mobile and web platforms: n = 3 (17.6%)
- Specialized diagnostic devices with digital connectivity: n = 1 (5.9%)

The predominance of basic mobile phone-based interventions (41.2%) reflects the pragmatic adaptation to technological infrastructure in many African settings.

Target Populations and Health Conditions

Population Characteristics

Age Groups:

- Infants (0-12 months): n = 3 studies
- Young children (1-5 years): n = 4 studies
- School-age children (6-12 years): n = 2 studies
- Adolescents (13-18 years): n = 5 studies
- Mixed age groups: n = 3 studies

Special Populations:

- Pregnant women and mothers (maternal-child health): n = 4 (23.5%)
- Adolescents at risk for HIV: n = 3 (17.6%)
- Children living with HIV: n = 3 (17.6%)
- Female sex workers: n = 1 (5.9%)
- Community populations in rural settings: n = 5 (29.4%)

Health Conditions Addressed**HIV/AIDS (n = 6, 35.3%):**

Studies focused on diverse aspects of HIV care:

- HIV testing and treatment initiation in rural Africa [22].
- Antiretroviral therapy adherence among adolescents [23].
- Home-based HIV testing interventions [24].
- Prevention of mother-to-child HIV transmission [25].
- HIV care retention through interactive text messaging [26].
- Second-line antiretroviral therapy adherence support [27].

Maternal and Child Health (n = 6, 35.3%):

- Surgical site infection diagnosis after cesarean section in Rwanda [28].
- Reproductive and child health outcomes in India with African relevance [29].
- Unintended pregnancy prevention among female sex workers in Kenya [30].
- Breastfeeding and child health among women living with HIV [31].
- Long-lasting insecticidal net uptake among pregnant women in Tanzania [32].

Tuberculosis (n = 2, 11.8%):

- Role of mothers in preventing tuberculosis in children [33].
- GeneXpert MTB/RIF screening on mobile HIV testing units in South Africa [34].

Other Conditions (n = 3, 17.6%):

- Childhood asthma and environmental exposures [35].
- Sexual risk reduction among adolescents [36].
- General child health surveillance and disease prevention

Effectiveness of Digital Health Interventions**Early Detection and Screening Outcomes****HIV Testing and Detection:**

Havlir et al. conducted a landmark cluster randomized trial in rural Uganda and Kenya evaluating a community health approach with mobile HIV testing. The intervention achieved remarkable results, with HIV testing rates reaching 89% in intervention communities compared to 82% in control communities ($p < 0.001$). Viral suppression rates were significantly higher in intervention arms (79% vs. 68%, $p < 0.001$), demonstrating that community-based digital health approaches can substantially improve both detection and treatment outcomes [22].

The Home-Based Intervention to Test and Start (HITS) trial in rural South Africa demonstrated that home-based HIV testing using mobile health workers increased HIV testing uptake among men from 48% to 67% (adjusted odds ratio [AOR] 2.23, 95% CI 1.87-2.66, $p < 0.001$) [24]. This intervention effectively addressed the critical gap in male HIV testing, a persistent challenge in African HIV programs.

Bassett et al. evaluated GeneXpert MTB/RIF screening integrated with mobile HIV testing units in South Africa. The intervention detected tuberculosis in 2.8% of participants screened, with same-day diagnosis enabling immediate treatment initiation. This integration of digital diagnostic technology with mobile health platforms demonstrated feasibility and effectiveness for dual HIV/TB screening [34].

Maternal and Child Health Screening:

Kateera et al. evaluated mHealth-supported surgical site infection (SSI) diagnosis by community health workers after cesarean section in rural Rwanda. The digital diagnostic support system enabled CHWs to accurately identify SSIs with a sensitivity of 89% and specificity of 91% compared to physician assessment. Early detection rates increased from 34% in standard care to 78% in the intervention group ($p < 0.001$), demonstrating substantial improvement in postoperative complication detection [28].

Vey et al. implemented targeted mobile health communication to increase long-lasting insecticidal net (LLIN) uptake among pregnant women in Tanzania. The intervention increased LLIN redemption rates from 58% in control areas to 79% in intervention areas (risk ratio 1.36, 95% CI 1.24-1.49, $p < 0.001$), demonstrating effectiveness of mHealth for malaria prevention in pregnancy [32].

Disease Management and Treatment Adherence**Antiretroviral Therapy Adherence:**

Ridgeway et al. conducted a systematic review of interventions to improve antiretroviral therapy (ART) adherence among adolescents in low- and middle-income countries. Digital health interventions, particularly SMS reminders and mobile phone-based support, demonstrated significant improvements in adherence rates. Studies reported adherence improvements ranging from 12% to 28% compared to standard care, with effect sizes of 0.3 to 0.7 [23].

Gross et al. evaluated a two-way mobile phone intervention for second-line ART adherence across multiple African countries. The intervention group achieved 83% adherence compared to 76% in the standard care group (adjusted difference 7%, 95% CI 2-12%, $p = 0.008$). Importantly, the intervention also improved virologic suppression rates (72% vs. 65%, $p = 0.02$), demonstrating that improved adherence translated to better clinical outcomes [27].

van der Kop et al. evaluated the WelTel Retain interactive text-messaging service for HIV care retention in Kenya. The intervention significantly improved 12-month retention in care (88% vs. 83%, adjusted risk ratio 1.06, 95% CI 1.01-1.11, $p = 0.01$). The intervention was particularly effective among younger patients and those newly diagnosed, addressing critical retention challenges in these populations [26].

Prevention of Mother-to-Child HIV Transmission:

Drake et al. designed a randomized controlled trial to evaluate mHealth strategies for optimizing adherence to Option B+ prevention of mother-to-child HIV transmission (PMTCT) in Kenya. The study protocol described a three-armed trial comparing one-way SMS, two-way SMS, and standard care. The intervention aimed to improve maternal ART adherence and

infant HIV-free survival through mobile phone support during pregnancy and postpartum periods [25].

Zunza et al. evaluated mobile phone text messaging combined with motivational interviewing for breastfeeding counseling among women living with HIV. The intervention significantly improved exclusive breastfeeding rates at 6 months (74% vs. 58%, $p = 0.003$) and reduced infant mortality (2.1% vs. 5.8%, $p = 0.04$), demonstrating substantial benefits for both maternal behavior change and child health outcomes [31].

Reproductive Health Management:

Ampt et al. conducted the WHISPER or SHOUT cluster randomized trial evaluating a mobile phone intervention for female sex workers in Kenya. The intervention reduced unintended pregnancy rates from 18.9 per 100 woman-years in control clusters to 14.2 per 100 woman-years in intervention clusters (adjusted incidence rate ratio 0.75, 95% CI 0.60-0.95, $p = 0.016$). The intervention also improved contraceptive use and sexual health knowledge [30].

LeFevre et al. evaluated a direct-to-beneficiary mobile communication program (Kilkari) in India, with findings relevant to African contexts. The intervention delivered stage-based audio messages to pregnant women and mothers. Results showed improvements in antenatal care attendance, institutional delivery, and early breastfeeding initiation, though effects varied by geographic region and socioeconomic status [29].

Health Outcomes

Mortality and Morbidity:

The most compelling evidence for digital health impact came from studies reporting mortality outcomes. Havlir et al. reported 3-year mortality rates of 1.3% in intervention communities compared to 1.7% in control communities, though this difference was not statistically significant ($p = 0.09$). However, among those with HIV, viral suppression rates were significantly higher in intervention groups, suggesting potential long-term mortality benefits [22].

Zunza et al. demonstrated significant infant mortality reduction in the mobile phone intervention group (2.1% vs. 5.8%, $p = 0.04$), representing a 64% relative risk reduction. This finding provides strong evidence that digital health interventions can impact critical child survival outcomes when effectively implemented [31].

Quality of Life and Functional Outcomes:

Several studies reported improvements in quality-of-life measures and functional outcomes, though these were typically secondary endpoints. Fiellin et al. evaluated a video game intervention for sexual risk reduction among minority adolescents and found significant improvements in HIV knowledge ($p < 0.001$), self-efficacy for condom use ($p = 0.004$), and intentions to use condoms ($p = 0.002$), suggesting potential for digital health education to improve health literacy and behavior [36].

Healthcare Utilization

Facility Visits and Follow-up:

Multiple studies reported improvements in healthcare utilization patterns. van der Kop et al. found that the WeTel Retain

intervention increased on-time clinic visits from 71% to 78% ($p = 0.02$) and reduced missed appointments. These improvements in care continuity are critical for chronic disease management, particularly for HIV and tuberculosis [26].

Kateera et al. demonstrated that mHealth-supported SSI diagnosis increased appropriate healthcare-seeking behavior, with 89% of women with suspected infections presenting to facilities within 48 hours compared to 56% in the control group ($p < 0.001$). This rapid response to complications can prevent serious morbidity and mortality [28].

Emergency Care and Hospitalization:

While limited data were available on emergency department utilization and hospitalization, available evidence suggested that digital health interventions may reduce preventable hospitalizations through improved disease management and early intervention. However, more research is needed to confirm these effects.

Implementation Factors and Contextual Considerations

Facilitators of Implementation

Technology Acceptability:

High acceptability of mobile phone-based interventions was consistently reported across studies. Ampt et al. reported that 94% of participants found the mobile phone intervention acceptable and 89% would recommend it to peers. Similarly, van der Kop et al. found that 96% of participants rated the text messaging service as helpful [26,30].

Community Health Worker Integration:

Integration of digital tools with community health worker programs emerged as a key facilitator. Kateera et al. demonstrated that CHWs could effectively use digital diagnostic tools with minimal training, achieving diagnostic accuracy comparable to clinicians. This finding supports task-shifting strategies enabled by digital health technologies [28].

User-Centered Design:

Studies that employed user-centered design principles and formative research reported better engagement and outcomes. LeFevre et al. emphasized the importance of culturally appropriate content, local language use, and message timing optimization for intervention effectiveness [29].

Barriers to Implementation

Infrastructure Limitations:

Several studies identified infrastructure challenges including unreliable electricity, poor network connectivity, and limited smartphone penetration in rural areas. Tanser et al. noted that network connectivity issues occasionally delayed data transmission in the HITS trial, though overall implementation was feasible [24].

Digital Literacy:

Variable levels of digital literacy, particularly among older adults and rural populations, posed challenges for some interventions. Studies employing basic SMS rather than smartphone applications reported fewer literacy-related barriers [27].

Sustainability and Cost:

Long-term sustainability concerns were raised in multiple studies.

While many interventions demonstrated effectiveness during research implementation, questions remained about sustainability after research funding ended. Cost-effectiveness analyses were limited, with only a few studies reporting detailed cost data [29].

Health System Integration:

Integration of digital health interventions with existing health information systems and clinical workflows presented challenges. Studies noted the need for stronger linkages between digital platforms and facility-based electronic health records to optimize care coordination [22].

Risk of Bias Assessment

Quality of Randomized Controlled Trials

Using the Cochrane Risk of Bias Tool 2 (RoB 2), the nine RCTs were assessed across five domains:

Low Risk of Bias (n = 6, 66.7%):

- Havlir et al.
- Ampt et al.
- Tanser et al.
- van der Kop et al.
- Zunza et al.
- Fiellin et al.

Some Concerns (n = 2, 22.2%):

- Gross et al. (some concerns regarding missing outcome data)
- LeFevre et al. (some concerns regarding outcome measurement in subgroup analyses)

High Risk of Bias (n = 1, 11.1%):

- Kateera et al. (high risk due to lack of blinding for outcome assessment, though this was inherent to the intervention design)

Quality of Non-Randomized Studies

Using the ROBINS-I tool, non-randomized studies were assessed:

Moderate Risk of Bias (n = 4, 80%):

- Bassett et al.
- Drake et al.
- Kouis et al.
- Vey et al.

Serious Risk of Bias (n = 1, 20%):

Ridgeway et al. (systematic review with heterogeneous included studies)

The review included one scoping review which was not formally assessed for bias but provided important contextual information about maternal roles in childhood tuberculosis prevention [33].

Publication Bias

Formal assessment of publication bias through funnel plots was not conducted due to the limited number of studies for each specific outcome and the heterogeneity of interventions and outcomes. However, the inclusion of studies with both positive and null findings suggests that publication bias may not substantially affect the conclusions.

Geographic Distribution and African Context Studies Conducted in African Countries

Seven studies (41.2%) were conducted specifically in African

countries:

Kenya (n = 3):

- Mobile phone intervention for female sex workers [30].
- WelTel Retain text messaging for HIV care retention [26].
- mHealth for Option B+ PMTCT adherence [25].

Rwanda (n = 1):

- mHealth-supported SSI diagnosis after cesarean section South Africa (n 2): [28].
- Home-based HIV testing intervention [24].
- GeneXpert TB screening on mobile HIV testing units [34].

Tanzania (n = 1):

- Mobile health for LLIN uptake among pregnant women [32].

Multi-Country Studies Including African Sites (n = 1):

- Community health approach in rural Uganda and Kenya [22].
- Two-way mobile phone intervention across multiple countries, including African sites [27].

Applicability to African Contexts

The remaining studies, while not conducted exclusively in Africa, provided evidence relevant to African contexts through similar population characteristics, comparable health system constraints, or transferable intervention approaches. The inclusion of these studies enriched the evidence base while maintaining focus on African applicability.

Synthesis of Evidence by Outcome Domain

Early Detection Domain

Strength of Evidence: Moderate

Digital health interventions demonstrated effectiveness for improving early detection across multiple disease categories. The strongest evidence came from HIV testing interventions and postoperative complication surveillance [22,24,28]. Effect sizes ranged from moderate to large, with risk ratios of 1.2 to 2.2 for detection outcomes.

Disease Management Domain

Strength of Evidence: Moderate to High

Substantial evidence supported digital health interventions for improving disease management, particularly for HIV/AIDS. Treatment adherence improvements of 7-28% were consistently reported across multiple studies [23,26,27]. The quality of evidence was strengthened by multiple high-quality RCTs with large sample sizes.

Health Outcomes Domain

Strength of Evidence: Low to Moderate

Evidence for health outcome improvements was more limited but promising. Significant mortality reductions were reported in one high-quality RCT, while other studies showed trends toward improved outcomes without reaching statistical significance. Longer-term follow-up studies are needed to strengthen evidence in this domain [31].

Healthcare Utilization Domain

Strength of Evidence: Moderate

Consistent evidence demonstrated improvements in healthcare

utilization patterns, including increased clinic attendance, reduced missed appointments, and improved care-seeking behavior. Effect sizes were generally moderate (10-20% improvements), with high-quality supporting evidence.

Discussion

This systematic review synthesized evidence from 17 studies examining the effectiveness of digital health innovations for early detection and management of childhood diseases in African contexts. The findings demonstrate that digital health interventions, particularly mobile health (mHealth) technologies, show considerable promise for addressing critical gaps in childhood disease prevention, detection, and management across diverse African settings. Seven studies (41.2%) were conducted directly in African countries, including Kenya, Rwanda, South Africa, and Tanzania, with interventions spanning from 2016 to 2025 and published in high-impact peer-reviewed journals.

The evidence reveals several key findings. First, digital health interventions significantly improved early detection rates across multiple disease categories, with particularly strong evidence for HIV testing and postoperative complication surveillance [22,24,28]. Effect sizes for detection outcomes ranged from risk ratios of 1.2 to 2.2, representing meaningful improvements in case identification that could translate to substantial population health benefits.

Second, disease management outcomes, especially treatment adherence, showed consistent improvements across multiple high-quality randomized controlled trials. Adherence improvements of 7-28% were documented for antiretroviral therapy with corresponding improvements in virologic suppression and clinical outcomes. These findings are particularly significant given the critical importance of sustained adherence for chronic disease management in resource-limited settings [23,26,27].

Third, while evidence for health outcomes such as mortality and morbidity was more limited, available data suggest meaningful impacts. The 64% relative reduction in infant mortality reported by provides compelling evidence that well-designed digital health interventions can influence critical survival outcomes [31]. However, longer-term follow-up studies are needed to fully characterize health outcome impacts.

Fourth, digital health interventions consistently improved healthcare utilization patterns, including increased clinic attendance, reduced missed appointments, and enhanced care-seeking behavior for complications. These intermediate outcomes are important indicators of health system strengthening and improved access to care.

Interpretation and Contextualization

Digital Health as a Health System Strengthening Tool

The findings of this review support the conceptualization of digital health not merely as a technological innovation but as a comprehensive health system-strengthening approach [7]. Digital health interventions addressed multiple health system challenges simultaneously: improving access to care through mobile platforms, enhancing quality through decision support tools, strengthening health information systems through real-time data collection, and optimizing human resources through

task-shifting enabled by digital tools [9].

The integration of digital technologies with community health worker programs emerged as a particularly promising strategy [28]. By equipping CHWs with digital diagnostic and communication tools, interventions extended the reach of health services to remote and underserved populations while maintaining quality through standardized protocols and remote supervision. This approach aligns with global strategies for achieving universal health coverage through primary health care strengthening [37].

PICO Framework Application

The application of the PICO framework proved valuable for structuring this systematic review and ensuring comprehensive evidence synthesis. The framework facilitated clear definition of:

Population: Children and adolescents aged 0-18 years in African contexts, with particular attention to vulnerable populations including children living with HIV, infants at risk for mother-to-child HIV transmission, and children in rural and remote areas with limited healthcare access.

Intervention: A diverse array of digital health innovations was identified, with mobile health (mHealth) interventions predominating (52.9% of studies). The emphasis on basic mobile phone platforms (SMS and voice calls) rather than smartphone applications reflects pragmatic adaptation to technological infrastructure realities in many African settings. This finding has important implications for intervention design and implementation, suggesting that effective digital health solutions need not require sophisticated technology platforms.

Comparison: Most high-quality studies employed rigorous comparison groups receiving standard care, enabling confident attribution of effects to digital health interventions rather than non-specific factors such as increased attention or research participation.

Outcomes: The review identified improvements across multiple outcome domains, with the strongest evidence for intermediate outcomes (detection, adherence, utilization) and emerging evidence for health outcomes (mortality, morbidity). This gradient of evidence strength reflects the longer follow-up periods and larger sample sizes required to detect health outcome changes.

Disease-Specific Insights

HIV/AIDS: The concentration of evidence in HIV/AIDS (35.3% of studies) reflects both the substantial burden of pediatric and adolescent HIV in Africa and the relatively mature state of digital health implementation in HIV programs [23]. The success of digital health interventions for HIV testing, treatment adherence, and care retention demonstrates proof-of-concept that may be transferable to other chronic conditions requiring long-term management.

The effectiveness of home-based testing interventions and mobile testing platforms addresses the critical challenge of reaching populations with limited facility access, particularly

men who are traditionally underrepresented in facility-based testing services [24, 34]. These approaches could be adapted for other screening and prevention services.

Maternal and Child Health: Digital health interventions for maternal and child health demonstrated effectiveness across diverse applications, including pregnancy care, postpartum monitoring, infant feeding support, and malaria prevention [28,31,32]. The integration of digital health with existing maternal-child health platforms such as antenatal care and postnatal follow-up provides natural touchpoints for intervention delivery.

The significant infant mortality reduction achieved through mobile phone-supported breastfeeding counseling highlights the potential for relatively simple digital interventions to impact critical child survival outcomes when addressing evidence-based practices such as exclusive breastfeeding. This finding warrants replication in diverse African contexts [31].

Tuberculosis: Evidence for digital health interventions in childhood tuberculosis was more limited (11.8% of studies), representing an important gap given the substantial burden of pediatric TB in Africa [33]. The successful integration of GeneXpert TB screening with mobile HIV testing platforms demonstrates the feasibility of dual screening approaches that could be expanded to other co-endemic conditions [34].

Implementation Science Insights

This review identified several critical implementation factors influencing digital health intervention success:

Technology Acceptability and Usability: High acceptability of mobile phone-based interventions was consistently reported (>90% in multiple studies), suggesting that technological barriers may be less substantial than sometimes assumed [26,30]. However, attention to user-centered design, local language support, and cultural appropriateness remained essential for maximizing engagement.

Infrastructure Considerations: While infrastructure challenges, including network connectivity and electricity access, were noted, most interventions successfully navigated these constraints through adaptive strategies such as offline functionality, SMS rather than data-dependent platforms, and solar charging solutions. These pragmatic adaptations offer lessons for future implementation efforts.

Human Resource Integration: The most successful interventions integrated digital tools with human support rather than attempting full automation. The combination of automated messaging with responsive human communication (two-way SMS, CHW follow-up for alerts) appeared more effective than one-way automated systems [26,27].

Health System Integration: Interventions that integrated with existing health system structures, workflows, and information systems demonstrated better sustainability prospects than standalone programs. However, achieving this integration often required substantial effort and collaboration with health authorities [22].

Comparison with Existing Literature

The findings of this review align with and extend previous systematic reviews of digital health in low- and middle-income countries. A 2016 systematic review by Agarwal et al. found similar patterns of effectiveness for mHealth interventions, with strongest evidence for medication adherence and appointment attendance. The current review adds substantial new evidence from recent high-quality trials and extends the evidence base to additional outcome domains, including early detection and health outcomes.

The emphasis on mobile phone-based interventions in African contexts is consistent with broader patterns in global digital health implementation, where mobile technologies have achieved greater penetration than internet-based platforms in resource-limited settings [7]. However, the rapid expansion of smartphone access and mobile internet connectivity in Africa suggests that future interventions may increasingly leverage more sophisticated platforms.

Strengths and Limitations

Strengths

This systematic review has several important strengths. First, the application of PRISMA 2020 guidelines ensures transparent and reproducible methodology aligned with current best practices for systematic review conduct and reporting [17]. Second, the use of the PICO framework provided clear structure for defining the research question and organizing evidence synthesis. Similarly, the inclusion of diverse study designs (RCTs, cluster RCTs, cohort studies) and intervention types provides comprehensive coverage of the digital health landscape. Furthermore, the focus on African contexts addresses a critical knowledge gap, as many previous reviews have not specifically examined African implementation experiences. Finally, the assessment of implementation factors alongside effectiveness outcomes provides actionable insights for practitioners and policymakers.

Limitations

Several limitations should be acknowledged. First, the search was limited to a single database (PubMed/MEDLINE) and English-language publications, potentially missing relevant studies published in other databases or languages. However, PubMed/MEDLINE provides comprehensive coverage of biomedical literature, and most high-quality African health research is published in English. Second, the heterogeneity of interventions, populations, and outcomes precluded meta-analysis for most outcomes, limiting the precision of effect estimates. Also, the limited number of studies for specific intervention-outcome combinations constrained subgroup analyses and exploration of effect modifiers. Similarly, many included studies had relatively short follow-up periods (6-12 months), limiting assessment of long-term effectiveness and sustainability. Furthermore, the review identified limited cost-effectiveness data, constraining economic evaluation of digital health interventions. Finally, the applicability of findings from non-African settings to African contexts involves some uncertainty, though efforts were made to assess contextual relevance.

Implications for Practice

Recommendations for Implementers

Based on the evidence synthesized in this review, several

recommendations emerge for digital health implementation in African childhood disease programmes:

- **Prioritize Mobile Phone-Based Interventions:** Given the strong evidence for effectiveness and high acceptability, mobile phone-based interventions (particularly SMS and voice calls) should be prioritized over more technology-intensive approaches, especially in resource-constrained settings.
- **Integrate with Community Health Practice:** Digital tools should be integrated with Community Health programmes to extend reach and enable task-shifting while maintaining quality through standardized protocols and remote supervision.
- **Employ User-Centered Design:** Interventions should be developed through participatory processes involving end-users, with attention to local languages, cultural appropriateness, literacy levels, and user preferences.
- **Combine Automated and Human Elements:** Hybrid approaches combining automated messaging with responsive human support appear more effective than fully automated systems and should be favored.
- **Plan for Health System Integration:** Early engagement with health system stakeholders and planning for integration with existing information systems and workflows are essential for sustainability.
- **Address Implementation Barriers Proactively:** Infrastructure challenges, digital literacy gaps, and sustainability concerns should be addressed through adaptive strategies including offline functionality, training and support, and sustainable financing mechanisms.

Policy Implications

For policymakers and health system leaders, the evidence supports several policy directions:

- **Invest in Digital Health Infrastructure:** Strategic investments in digital health infrastructure, including mobile networks, health information systems, and interoperability standards, can enable scalable digital health implementation.
- **Develop Supportive Regulatory Frameworks:** Clear regulatory frameworks for digital health technologies, data privacy and security, and quality assurance can facilitate responsible innovation while protecting patient safety.
- **Integrate Digital Health into National Health Strategies:** Digital health should be integrated into national health strategies, disease-specific programs, and health system strengthening initiatives rather than treated as standalone interventions.
- **Support Capacity Building:** Investments in digital health literacy for healthcare workers, managers, and communities can enhance intervention effectiveness and sustainability.
- **Promote Evidence Generation:** Support for rigorous evaluation of digital health interventions, including long-term follow-up and cost-effectiveness studies, can strengthen the evidence base for decision-making.

Future Research Directions

This review identified several critical gaps and priorities for future research:

- Research with extended follow-up periods (≥ 2 years) is needed to assess the sustainability of effects and long-term health outcomes, including mortality and morbidity.

- Comprehensive economic evaluations comparing costs and benefits of digital health interventions versus standard care are urgently needed to inform resource allocation decisions.
- Studies examining implementation strategies, adaptation processes, and factors influencing scale-up success can inform broader dissemination efforts.
- Head-to-head comparisons of different digital health approaches (e.g., SMS vs. smartphone apps, one-way vs. two-way communication) can guide intervention design choices.
- Research on digital health for childhood diseases beyond HIV/AIDS is needed, particularly for tuberculosis, malaria, pneumonia, diarrheal diseases, and non-communicable diseases.
- More research on digital health for disease prevention, health promotion, and early childhood development can expand the evidence base beyond treatment-focused interventions.
- Given the unique challenges of adolescent health and the high digital engagement of adolescents, research specifically targeting adolescent populations is warranted.
- Studies examining integration of digital health across multiple disease areas and health system functions can inform holistic implementation strategies.
- Research in West, Central, and North African countries is needed to complement the existing evidence base from East and Southern Africa.
- Additional research in rural and remote settings where healthcare access challenges are most acute can inform strategies for reaching underserved populations.
- Digital health may offer particular advantages in fragile and conflict-affected settings, warranting focused research attention.

Conclusion

This systematic review provides comprehensive evidence that digital health innovations, particularly mobile health technologies, demonstrate considerable effectiveness for improving early detection and management of childhood diseases in African contexts. The evidence base has strengthened substantially in recent years, with multiple high-quality randomized controlled trials demonstrating improvements in detection rates, treatment adherence, healthcare utilization, and, in some cases, health outcomes, including mortality.

The successful implementation of digital health interventions across diverse African countries and health system contexts demonstrates feasibility and provides proof-of-concept for broader scale-up. However, realizing the full potential of digital health for childhood disease control in Africa will require sustained attention to implementation challenges, including infrastructure development, health system integration, capacity building, and sustainable financing.

The application of the PICO framework and PRISMA 2020 guidelines in this review ensures that the evidence synthesis is rigorous, transparent, and reproducible. The findings provide actionable evidence for policymakers, implementers, and researchers working to leverage digital technologies for child health improvement in Africa.

As digital connectivity continues to expand across the

African continent and digital health technologies continue to evolve, opportunities for innovation and impact will grow. Future research should focus on long-term effectiveness, cost-effectiveness, implementation science, and expansion to underrepresented disease areas and geographic regions. With continued investment, innovation, and evidence generation, digital health can contribute substantially to achieving child health goals and universal health coverage across Africa.

Declaration of AI Use

All authors contributed to the conception, design, literature review, analysis, interpretation, and critical revision of this manuscript. SciSpace supported literature screening and organisation, while PaperPal and ChatGPT were used solely for language refinement, clarity, grammar, and reference formatting. These AI tools served only as supportive aids and did not replace the authors' independent judgement or scholarly decisions. All AI-assisted outputs were reviewed, verified, and approved by the authors, who retain full responsibility for the accuracy, integrity, originality, and final content of the manuscript.

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Conflicts of Interest

The authors declare no conflicts of interest.

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