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SYSTEMATIC REVIEW

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Effect of digital interventions on adherence to the management of type 1 diabetes mellitus patients: a systematic review

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Abstract

Introduction Digital health interventions have gained prominence in the management of chronic diseases like Type 1 Diabetes Mellitus (T1DM), helping patients adhere to their treatment plans. However, the effectiveness of these interventions in improving adherence to T1DM management varies globally.

Objectives To systematically review existing digital interventions designed to improve adherence to T1DM management. To identify key features of digital tools that enhance adherence and glycaemic control in T1DM patients.

Main Outcome Measures Primary outcomes were improvements in patient adherence, measured by frequency of insulin administration, self-monitoring of blood glucose, and HbA1c levels. Secondary outcomes included patient satisfaction and engagement with digital interventions.

Methods A systematic review of randomized controlled trials (RCTs) was conducted using the PICO framework. The review encompassed studies from various global regions. Studies included T1DM patients across different age groups. Databases such as PubMed, Cochrane, and Ovid were searched for relevant studies.

Results A total of 12 randomized controlled trials (RCTs) were included in this review, focusing on improving adherence in T1DM patients. The digital interventions evaluated included mobile health applications, continuous glucose monitoring, telemedicine platforms, and educational video games. Most studies demonstrated significant improvements in patient adherence behaviours, such as insulin administration and self-monitoring of blood glucose, reductions in HbA1c levels were also noted.

Discussion The improvements in HbA1c as seen in this review for individuals with T1DM are in line with findings from prior studies. The evidence showed that digital health technologies could enhance glycaemic control. These findings are in line with other studies where real-time data monitoring equipment of the emergent CGM systems and mobile apps facilitated accurate and timely modification of diabetes self-management. The reviewed studies

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also highlighted the effectiveness of digital technology-targeted interventions in enhancing the aspect of self-management and health behaviour among T1DM patients. These results are also aligned with the behavioural change theories which highlight the significance of education, perceived self-ability and continuous feedback in adopting good health behaviour.

Conclusions Digital interventions have a positive impact on adherence to T1DM management and glycaemic control. Their application, particularly in low-resource settings, holds great potential for improving health outcomes.

Clinical trial number Not applicable.

Plain language summary The aim of this review was to look at how mobile applications among other digital tools can assist people living with Type 1 Diabetes (T1DM) through continuous glucose monitoring to manage their health condition in a better way. For this purpose, we reviewed 12 different studies and found that interventions delivered through digital tools enhanced patients' adherence to their treatment by helping them lower the blood sugar levels as measured by HbA1c levels. Main findings reflected how digital tools improved health behaviours and self-management of T1DM. This was facilitated by real-time data monitoring and feedback for the diabetes care. In conclusion, Digital health interventions have the potential to positively impact the T1DM treatment leading to improved health outcomes especially in low resource settings.

Key points

- Telemedicine-based educational models improved the understanding of the disease.
- More learning about normal, hyperglycaemic, and hypoglycaemic blood glucose levels.
- Patients receiving telemedicine services adhere to the treatment regimens.
- Major outcome of digital health intervention – improved glycaemic levels of patients.

Keywords Type 1 diabetes mellitus, Digital health interventions, Mobile applications, Continuous glucose monitoring, Adherence, Glycaemic control, Systematic review, Telemedicine, Low-resource settings

Background

Diabetes Mellitus (DM), one of the most prevalent non-communicable diseases, is expected to rank as the seventh leading cause of death globally by 2030 [1]. According to the International Diabetes Federation (IDF), in 2021 approximately 6.7 million deaths were attributable to diabetes, while the global incidence of DM stands at 537 million people and is expected to reach 783 million by 2045 [2]. DM impacting global health is on the rise despite prevention measures across the world underscoring the importance of appropriate solutions [3].

Type 1 Diabetes Mellitus (T1DM) is an autoimmune disease resulting in insulin dependence [4]. The underlying pathological process results in immune systems T cells destroying the pancreatic beta cells leading to a gradual decrease in the production of insulin [5]. T1DM constitutes about 10% of all DM cases and can manifest at any age, though it is most seen in children and young adults [6]. The incidence of T1DM has been increasing over the past few decades, and it is estimated to affect approximately 1.1 million children and adolescents between the ages of 0–19 years globally [7]. According to the IDF Diabetes Atlas, the global population of individuals with T1DM reached 8.75 million in 2022 [8]. Of these, 1.52 million people were under the age of 20, 5.56 million were aged between 20 and 59 years, and 1.67 million were older than 60 years old [8]. It remains one of the most prevalent endocrine diseases globally, with diagnoses most commonly occurring in young people [9].

With severe long-term consequences of hyperglycaemia, TIDM is complex and time-intensive to manage compared to other chronic diseases [10]. Living with T1DM entails a substantial disease burden and adverse psychosocial effects [11]. Late-stage complications of T1DM include macrovascular complications such as cerebrovascular and coronary heart disease, microvascular complications such as retinopathy, neuropathy, nephropathy, and peripheral vascular disease, and an increased risk of foot ulcers and amputations [12, 13]. Patients with T1DM need to manage their glycaemic levels effectively to reduce the risk of diabetes related complications and to better manage associated health conditions [14]. There are several guidelines for specific medical treatments and practices advocated to prevent and delay the complications in patients with T1DM [15].

DM care guidelines contain significant measures of primary prevention involving appropriate dietary and physical activity, promoting healthy lifestyle, education and interim health counselling and related activities [16]. Insulin is recommended as a treatment for managing T1DM [17]. According to the current recommendations and evidence, lifestyle interventions (diet control, exercise and stress management) are considered primary prevention and a part of the management approach for T1DM patients [18]. Several research papers have shown the efficacy of lifestyle modification in the management of obesity and enhancing glycaemic control, the aspects of which may be measured by glycosylated haemoglobin

(HbA1C) [19]. The American Diabetes Association (ADA) and the European Association for the Study of Diabetes (EASD) acknowledge HbA1C as the preferred target for the therapy of DM [17]. The study by Batista et al. identifies education and self-management support as necessary in T1DM given that there are various behaviours and medical procedures required to manage the illness [20]. Self-care, for instance, can reduce the personal impact of the disease by a very large extent [21]. It was also observed the educational and support needs of individuals vary due to the different lifestyles [22]. Diabetes care management includes management of blood glucose, following a proper diabetes medication schedule, control of food intake, exercise and gaining optimal levels of diabetes self-care skills [23, 24]. This requires an integrated care plan as every individual is unique as to how their body metabolises insulin and reacts to diet and exercise [25]. Therefore, self-reflection and individual adjustments are essential when it comes to managing T1DM [25]. Moon et al., mentioned in their study that for patients with T1DM, lifestyle modifications, including proper nutrition, regular physical activity, and smoking cessation, are crucial for effective diabetes management [26]. Empowering patients through diabetes self-management education and addressing psychological aspects such as diabetes-related distress, quality of life, and depression are essential components of successful treatment [27].

Gee et al. highlighted the accessibility to internet and digital advancements as facilitators of health promotion and chronic disease management such as DM [28]. The study also reflected on a notable increase in scientific literature exploring the role of information and communication technologies (ICT), digital health, (d-health), mobile health (m-health), and electronic health (e-health) in supporting lifestyle modifications for individuals with DM [28, 29]. In this context, digital health applications have become increasingly important in implementing diabetic management principles and preventing diabetic complications, as they are both effective and cost-efficient [29]. These apps support patients in self-management, assisting them in achieving their treatment goals [29]. Advancements in diabetes technology offer promising new solutions for closely monitored disease management [29]. Despite these advances, a significant number of individuals with DM do not achieve their treatment goals [19].

Patients generally need to assimilate a vast amount of information and develop practical skills and competencies [21]. They must adhere to a rigorous and complex daily regimen, which includes monitoring blood glucose levels, estimating calorie intake, and administering insulin multiple times a day [21]. The management of T1DM is particularly challenging for children and adolescents, as they are in a vulnerable stage of development [30]. They face psychosocial challenges such as stigma, stress, burnout, peer relationships, and diabetes-related family conflicts [30]. This "diabetes distress" encompasses feelings of hopelessness, frustration, guilt, anger, or fear [31]. Enhancing T1DM management through digital tools can facilitate more direct engagement with adolescents and adults outside the clinical settings, thereby addressing their daily challenges more effectively [22]. The rapid development of digital tools has significantly transformed healthcare over the past decade and is now an integral part of adolescents as well as adults' daily lives, making it a viable support for managing chronic diseases [32]. The study by Cochrane indicates 89% of young people are online daily, averaging 4.3 hours, highlighting the potential for digital tools to aid adolescents with common chronic conditions such as T1DM [33].

Digital health encompasses various information technologies used in healthcare, including mobile devices [16]. Like other health sectors, digital health has been successfully utilised in diabetes self-management education and support (DSMES) [34]. Nkhoma et al. demonstrated that social media-led digital interventions have also shown success in improving clinical outcomes, prompting many healthcare organisations to explore social media-assisted chronic disease management [35]. This growing use of social media in chronic disease care requires further independent and comprehensive analysis [36]. Mobile health interventions are extensively used in DSMES with varying degrees of effectiveness, while web-based interventions have also proven effective in enhancing various clinical and psychosocial outcomes [37]. Promoting adherence to management and diabetes self-management skills through age-appropriate digital strategies could be crucial in preventing complications, improving quality of life, and positively impacting clinical outcomes [26]. This increasing evidence suggests the potential benefits of digital interventions across various health conditions [20]. Studies have indicated that low-intensity brief interventions, such as those for smoking cessation, delivered through digital applications, can be effective [38]. Conversely, higher-intensity face-to-face interventions, whether conducted in group settings or on a one-to-one basis, have traditionally been considered the gold standard for diabetes self-management training [39]. However, despite these benefits, some evidence indicates that digital interventions are not always effective in improving health outcomes, particularly in the absence of personal interactions [40]. A review by Chatterjee et al. highlighted that technology-based interventions, including web-based methods, were less effective than face-to-face sessions [41].

A significant question remains regarding the effectiveness of digital interventions. Rohilla et al. mentioned in their study that while many digital applications are available for patients, there is not enough evidence regarding the utility of these apps [42]. This highlighted the importance of further research to establish the efficacy of digital interventions in the healthcare of patients with T1DM. It is important to fill this gap to enable the adoption of digital applications in the context of healthcare. This review seeks to fill the gap by providing a comprehensive synthesis of the available literature and evaluate the effects of various digital health interventions for patients suffering from T1DM. Digital health interventions have the potential to transform the management of chronic diseases by supporting patients in adhering to their treatment plans [43]. This review builds on the understanding of adherence challenges in T1DM management by systematically reviewing the effectiveness of digital interventions across various global contexts. The primary focus of this systematic review is to assess how digital tools—such as mobile health (mHealth) applications and telemedicine have been employed to improve adherence in T1DM patients. The review highlights both the successes and limitations of these technologies, with particular emphasis on their applicability to low- and middle-income countries like Pakistan. By synthesizing the findings from existing literature, this review provides critical insights into the key factors that make digital interventions effective and the gaps that remain in developing countries, where access to technology and healthcare services may be limited.

Aims and objectives

The overall aim of this study is to review and evaluate the literature regarding the role and effectiveness of digital health solutions in improving adherence to the management of T1DM patients. Therefore, this research intends to identify how digital health technology improves adherence to the management of T1DM and the key outcomes of glycaemic control and other secondary outcomes for individuals with T1DM.

Methods

The PRISMA Statement and checklist (Preferred Reporting Items for Systematic Reviews) was adopted and followed [44, 45]. A protocol was registered with the International Prospective Register of Systematic Review PROSPERO (reg. NR: CRD42022358723) on 22nd September 2022.

Eligibility criteria

The authors defined in advance the inclusion and exclusion criteria for this review. Quantitative Studies demonstrating the therapeutic effectiveness of diabetes-specific digital technologies in patients diagnosed with T1DM were included. (1) All those studies published before 2025 to locate and incorporate all the possible literature, considering the dynamic nature of the digital health field. (2) Only research published in English was considered due to limited resources for reliable translation. (3) This systematic review only included publications that reported adherence to T1DM management as an outcome. (See Table 1).

Information sources

Systematic and comprehensive electronic searches were performed in five databases including Medline (via PubMed), The Cochrane Library, EMBASE (via Ovid), Web of Science (Wolters and Cluver) and CINAHL.

Table 1 Inclusion and exclusion criteria

Criterion	Inclusion	Exclusion
Study settings	- Participants from any location worldwide	- None related to geographical location
Study Population	No specific demographic restrictions	- None beyond standard study exclusions
Type of Publication	Original articles in peer-reviewed journals.	- Studies published as comments, editorials and review - Studies are published as abstracts only, and full text is not available. - Studies that are non-original publications, books, thesis, editorials, commentaries, posters, letters, or abstracts. - Duplicate studies - Research studies that were either unavailable or incapable of being transcribed into the English language at all.
Language	English	All other languages
Focus of study	- Clinical Trials conducted on Type 1 Diabetes Mellitus Patients of any age, gender or place. - Studies which used any type of digital intervention (computers, web-based applications, mobile phones, wearable sensors, or any other technological platforms). - Studies conducted at hospitals (public/private or both) or in community settings, rural/urban or both. - Studies reporting adherence to T1DM management and other mentioned secondary outcomes.	- Studies that included both T1DM and T2DM patients. - Studies conducted on populations with disabilities or pregnant patients. - Studies conducted on T1DM patients who are using CGM/Insulin Pumps.

Table 2 Pico framework

Population:	All patients with T1DM, irrespective of their age or demographic background.
Intervention:	Digital intervention solutions that can help in improving adherence to the management of T1DM. This ranges from mobile applications, wearable devices, online platforms, and potentially remote telemedicine interventions.
Comparison:	Nil
Outcome:	Primary Outcome • Adherence to the management of T1DM patients. Secondary outcomes • Glycaemic control is assessed by glycosylated haemoglobin (HbA1c). • diabetes self-management behaviours, which include medication (insulin) compliance, adequate dietary and exercise compliance, adherence to blood glucose monitoring and other associated aspects.

Table 3 Search terms, keywords and boolean operators for the databases

Population	((type 1 diabetes mellitus[MeSH Terms]) OR (juvenile onset diabetes mellitus[MeSH Terms])) OR "Insulin dependent"[tiab] OR (Insulin-Dependent[tiab]) OR ("Insulin dependent diab*"[tiab] OR "Insulin-dependent diab*"[tiab] OR "juvenile onset diab*"[tiab]) OR ("juvenile onset"[tiab]) OR (juvenile-onset[tiab]) OR (IDDM[tiab]) OR ("sudden onset diab*"[tiab]) OR ("sudden-onset diab*"[tiab]) OR ("Type 1 Diab*"[tiab]) OR ("autoimmune diabetes"[tiab]) OR ("autoimmune diab*"[tiab]) OR "Ketosis-Prone Diab*"[tiab] OR "Ketosis Prone Diab*"[tiab] OR T1DM[tiab] OR (insulin depend or insulindepend[tiab]) NOT (non-insulin depend[tiab])
Intervention	((telehealth[MeSH Terms])) OR (telecommunication[MeSH Terms]) OR "Mobile health" [tiab] OR "mHealth" [tiab] OR "eHealth" [tiab] OR "digital health" [tiab] OR "health app" [tiab] OR "app" [tiab] OR "mobile application" [tiab] OR "mobile app*" [tiab] OR smartphone [tiab] OR "smartphone" OR "mobile phone" [tiab] OR "cell phone" [tiab] OR "tablet" [tiab] OR "web-based" [tiab] OR "online" [tiab] OR "internet" [tiab] OR "mobile application" [tiab] OR mobile app* [tiab] OR tele*
Outcome	"self-management" OR "medication" OR "insulin" OR "compliance" OR "adequate diet" OR "exercise" OR "physical activity" OR "adherence" OR "blood glucose monitoring" OR "glycaemic control" OR "glycaemic status" OR "HbA1c" OR "quality of life" OR "improved glucose level" OR "satisfaction"

In addition, grey literature searches were conducted in Google Scholar. A search of the reference lists of all included studies was also carried out to recognise any relevant research missed by electronic and manual searches. The authors updated the search in all databases on the 22nd of Aug,2025 with no new relevant results according to the eligibility criteria.

Search strategy

Following the PICO framework (Table 2), synonyms and related terms related to Diabetes Mellitus, digital health interventions, adherence and health outcomes were used to search for pertinent literature. The search strategy utilised a mix of controlled vocabulary, such as Medical Subject Headings (MeSH) for PubMed, and free text in titles and abstracts. The block-building approach was also utilised, in which keywords and terms were combined with Boolean operators (i.e., AND and OR) to refine the search progressively and ensure relevant results. The search periods were specified for all databases involved. The search strategies were modified while searching according to each database. The search was limited to publications classified randomised controlled trials. No filters were applied to restrict the geographical locations of studies during the search. Thus, an extensive literature search with a strategy that covered T1DM, adherence and different types of digital intervention was carried out. Exclusions were applied to publications without abstracts, abstract-only publications, and those with non-retrievable full texts. For grey literature searches, a similar search strategy was implemented as was used for the databases. All search terms, keywords and Boolean operators for the databases are provided in the Table 3.

Study selection process

After conducting an electronic search in the databases, the reviewer transferred the references to Mendeley reference management software version 2.9 5.0. Upon uploading all references and eliminating any duplicate entries from the outcome of the search, the reviewer examined the articles with the help of the online systematic review application, Rayyan. Two reviewers assessed all titles and abstracts to extract papers based on predetermined criteria for eligibility and excluded all irrelevant records. Only those studies were selected which were relevant to the research question and were published in peer-reviewed journals. The PRISMA Flow Diagram (Fig. 1) was used to extract the most relevant studies for inclusion in this review.

Data collection process and data items

Two reviewers (AR* and SH**) independently scanned the electronic records to identify potentially eligible trials. A predesigned data extraction sheet (Table 4, Additional file 1) was used to extract and sort these trials independently. All discrepancies were resolved in discussion with a third reviewer (MJ***). The studies were synthesised based on their outcomes, as the therapeutic approach prioritises enhancing individual outcomes through the intervention. All the relevant information from the publications that were reviewed were extracted and recorded in a structured manner. Extracted data

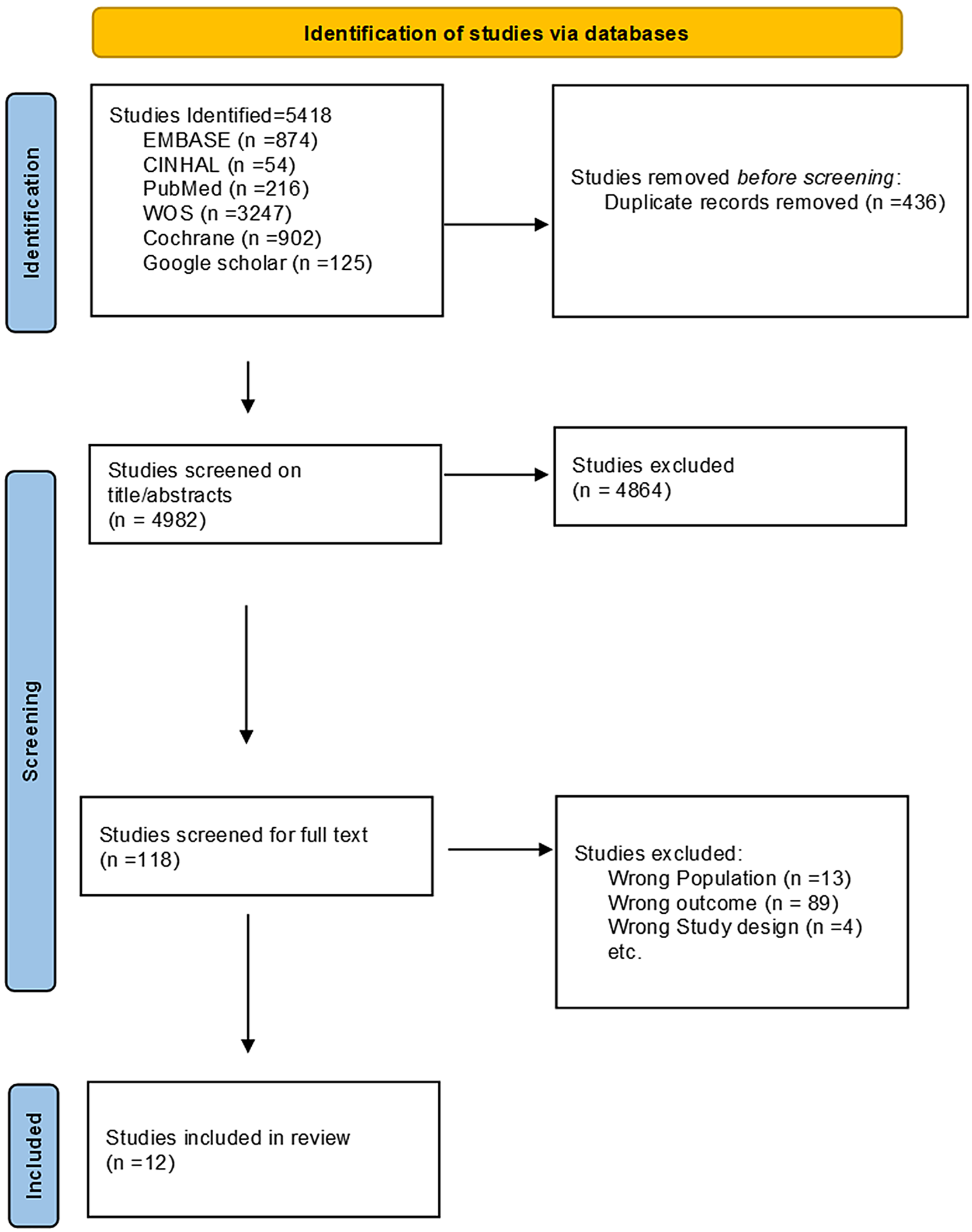

Fig. 1 PRISMA flowchart. *MA = Asif Rehman (1st Reviewer). **SH = Sana Hussain (2nd Reviewer). ***MJ = Mohammad Jawad (3rd Reviewer)

included: (1) the title (2) author (3) publication year (4) study period (5) study design (6) sample demographics (7) type of digital intervention (8) outcomes. The outcomes for each study were documented in a pre-designed data extraction Excel spreadsheet (Table 4). To obtain any pertinent missing information, the writers of those articles were contacted by email. If an author failed to react, reminder emails (up to a maximum of two) were sent. If the author still did not reply, the article was excluded from the review process.

Study selection

From 5418 studies identified through five databases PubMed (*n* = 216), Cochrane (*n* = 902), CINAHL (*n* = 54), Web of Science (*n* = 3247) Embase (*n* = 874), and via other methods (grey literature), the authors identified

Table 4 Data extraction table

Author	Aim	Setting	Sample size	Age	Study design	Digital intervention	Intervention period	Data collection method	Outcomes	Main findings	Conclusion
Rafeezadeh et al., 2019 (184)	To find out how a diabetic self-management instructional video game influenced kids with type 1 diabetes adherence to self-care routines.	**Iran** (Endocrine Department of Akbar Children's Hospital Mashhad)	68	8–12 years **I** = 9.9±1.4 **C** = 10.4±1.2	RCT	Interactive video game	3 months	20-item researcher-made Diet and Exercise Regimen Adherence Questionnaire	Adherence to self-care improved	**Mean self-care score** **I** = 82.9±7.8 **C** = 77.3±7.7 p = 0.57 **Adherence to** diet regimen**(I)** = 38.6±5.7 diet regimen**(C)** = 38.1±2.4 exercise regimen **(I)** = 35.1±5.7 exercise regimen **(C)** = 35.9±7.4 **HbA1C** **I** = 7.3±1.5 **C** = 7.7±1.4 p = 0.027	The instructional video game's design has the potential to greatly raise kids' self-care scores. It was recommended that future research compare online and offline video games since video games on the Internet may be easily altered and updated.

Table 4 (continued)

Author	Aim	Setting	Sample size	Age	Study design	Digital intervention	Intervention period	Data collection method	Outcomes	Main findings	Conclusion
Banu et al., 2023 (185)	To evaluate the impact of 2 interventions MHE and THE on adherence to the seven characteristics of diabetic self-management.	**Bangladesh** Thakurgaon district.	990	47.67 ± 9.28 years **MHE** = 47.58 ± 9.59 **THE** = 47.46± 8.72 **Control** = 47.97± 9.51	RCT	MHealth Education **(MHE)** Traditional Health Education **(THE)**	12 months	Face-to-face interview using a semi-structured questionnaire	Adherence to self-management	**MHE** and **THE** groups demonstrated substantial ($p < 0.01$) improvements in knowledge, adherence to self-management, and health outcomes as compared to the **control** group. **The MHE** group showed more significant improvement than **THE** for adherence to the drug, physical exercise, follow-up visits and blood glucose tests and stopping tobacco. **T**he group showed a more significant improvement in diet and foot care **MHE** was more economical.	For peripheral diabetes patients in Bangladesh, the MHE intervention outperformed the THE intervention in terms of increasing knowledge, encouraging adherence to the majority of self-management guidelines, and improving health outcomes. Peripheral regions of LMICS benefit from MHE involvement as well. Regarding the self-management of type 1 diabetes along with other non-communicable illnesses in low- and middle-income countries, this intervention might be replicated.

Table 4 (continued)

Author	Aim	Setting	Sample size	Age	Study design	Digital intervention	Intervention period	Data collection method	Outcomes	Main findings	Conclusion
Kotsani et al., 2018 (186)	This study aims to assess how telenursing affects T1DM patients' adherence to glycaemic management and glucose self-monitoring	**Northern Greece**	94	18–39 **I** = 26.35(±7.36) **C** = 27.63 (±7.25)	RCT	Telenursing Services	3 months	Recording glucose level measurement	Adherence to monitoring blood glucose	Total number of **glucose measurements missed** per day **I** = 54.1% **C** = 69.7% **p**-value < 0.001 **HbA1C** decreased over time **I** = 8.3 ± 0.6—7.8±1% (p = 0.03) **C** = 8.1±1.2—7.9±0.8%(p = 0.15) **Blood glucose level** **Morning**; 93.18 ± 13.30 mg/dl vs. 105.17 ± 13.74 mg/dl, $p < 0.005$, **Pre-prandial**; 114.76 ± 9.54 mg/dl vs. 120.84 ± 4.05 mg/dl, $p < 0.005$ **Post-prandial**: 193.35 ± 25.36 mg/dl vs. 207.84 ± 18.80 mg/dl, $p < 0.005$.	Compared to patients receiving standard clinic care, those in the intervention group experienced improved glucose control and more frequent self-monitoring. The research's conclusions suggest that telenursing can inspire T1DM patients to take better care of their condition.

Table 4 (continued)

Author	Aim	Setting	Sample size	Age	Study design	Digital intervention	Intervention period	Data collection method	Outcomes	Main findings	Conclusion
Di Bartolo et al., 2017 (187)	Comparison between the iBGStarTM+ DMApp (experimental metre + telemedicine system) (iBGStar) with a conventional glucose metre (Control) in adolescents and young people with type 1 diabetes. The objective of this study was to demonstrate the superiority of iBGStar^{TM} DMApp as a component of diabetes management versus traditional blood glucose self-monitoring systems in: • Reducing HbA1c levels after 6 months of follow-up; Improving the compliance to SMBG after 6 months.	**Italy** 21 diabetes clinics	182	17.7 ± 3.0 years **I** = 17.6±3.1 **C** = 17.8±3.0 **p** = 0.56	RCT (Multi-center, open-label)	Ibgstartm+ dmapp (experimental meter + telemedicine system) (ibgstar)	12 months	• SMBG frequency • HbA1c • Quality of life • Audit of diabetes-dependent quality of life (ADDQoL 19) • Diabetes Quality of Life for Youth (DQOLY) • Visual analogue scale (VAS)	Self-monitoring blood glucose (SMBG) frequency improved	After six months, In both groups, the **mean daily SMBG readings** rose from 1.1 to 2.3 without causing a decline in quality of life. After 6 months **HbA1c levels** iBGStar = −0.44 ± 0.13% Control = −0.33 ± 0.13% (p = 0.51). After 6 months, **compliance to SMBG** iBGStar = 53.6% Control = 55.0% p = 0.85 **HbA1c levels in compliant participants** iBGStar −0.60% ± 0.23 Control = −0.41% ± 0.21 (p = 0.31).	The conventional metre was not much better than iBGStar. The lack of difference was caused by comparable improvements in both groups, which included a significant rise in SMBG compliance and a little but significant decrease in HbA1c levels. Increasing the number of SMBG tests per day from one to two was linked to a decrease in HbA1c in both groups, regardless of the approach, without the need for pharmaceutical treatments. Finding innovative technologies that are both efficient and well-liked by patients is one way to increase patient adherence to diabetes treatment.

Table 4 (continued)

Author	Aim	Setting	Sample size	Age	Study design	Digital intervention	Intervention period	Data collection method	Outcomes	Main findings	Conclusion
Howe et al., 2005 (188)	The research aimed to evaluate the effects of 3 nursing treatments (SC, ED, ED+TCM) on glycaemic control, diabetes knowledge, adherence and parent-child teamwork in children with T1DM.	**USA** Paediatric Diabetes Center, Philadelphia	75	12.5 ± 3.4 years,	RCT	**SC** = Standard care **ED** = Education **(ED + TCM)** = Education and telephone case management	6 months	• Adherence checklist (ADH) • Hemoglobin A1c measurements • Demographic questionnaire • Diabetes Knowledge Test (KNOW) • Parent-child teamwork assessment (TEAM)	**HbA1c** **KNOW** Diabetes knowledge **TEAM** Parent-child teamwork **ADH** Adherence	ADH **SC** = 51.2 ± 25.1—-49.2±28 **ED** = 49.8±27.5—-54.1±23.9 **ED+TCM** = 48.3±19.7—72.3±19.7 ED + TCM = improved by 24% SC = improved by 2% (t = 3.9, p = 0.0002) **HbA1c** SC = 10.2 ± 1.4—-9.9±1.6 ED = 10.1±1.2—-9.7±1.9 ED+TCM = 10.0±1.4—9.5±1.7 There were no significant differences among 3 groups F [4 71] = 0.12, p = 0.97 **KNOW** SC = 83.6 ± 10.0—-83.7±10.2 ED = 81.6±12.5—-84.9±12.1 ED+TCM = 83.8±11.3—88.1±10.1 No statistically significant differences were found regarding KNOW change scores from baseline to 6 months among the 3 groups. **TEAM** **SC** = 61.2 ± 21.0—-55.8±27.5 **ED** = 53.0±26.4—-62.2±23.5 **ED+TCM** = 55.0±28.7—78.5±21.4 ED + TCM = improved by 24% SC = reduced by 5.4% (t = 3.8, p = 0.0003).	While HbA1c levels improved significantly but not significantly as a consequence of telephone case management, the adherence measure was significantly impacted. The majority of diabetes clinical research focuses on raising HbA1c levels. There is a need to stop focusing only on the HbA1c to identify the more modest and subtle behavioural changes that are encouraging moves in the direction of improved diabetic control. This modification could be a step in the right direction towards better diabetes treatment adherence and, eventually, improved diabetes management.

Table 4 (continued)

Author	Aim	Setting	Sample size	Age	Study design	Digital intervention	Intervention period	Data collection method	Outcomes	Main findings	Conclusion
Esmatjes et al., 2014 (189)	The effect of an Internet-based telematic system on the clinical and monetary management of individuals with T1DM were assessed in this research.	**Spain** five hospitals	154	I = 32.2±10.1 C = 31.5±9.0	RCT	2 face-to-face + 5 telematics appointments Vs 7 face to face appointments	6-month	• **Adherence** Diabetes Self-Care Inventory-Revised • **Quality of Life** DRQol EuroQOL • **Knowledge** Diabetes Knowledge Questionnaire (DKQ2)	Adherence (Diabetes Self Care inventory) to treatment improved in both groups.	**Adherence (SCI-R)** **I** = 61.3±12.0—66.1±11.0 ($p = 0.003$) **C** = 64.1±10.7—69.8±9.6 ($p < 0.001$) **HbA1C** **I** = 9.2±1.5—8.7±1.5 ($p < 0.001$) **C** = 9.2±0.9—-8.6±0.9 ($p < 0.001$) **Knowledge (DKQ2)** **I** = 24.5±4.6—26.1—4.6 ($p = 0.008$) **C** = 24.8±4.4—-26.8±4.0 ($p < 0.001$) **Quality of life (EuroQol)** **I** = 65.0±18.8–69±18.7 ($p = 0.904$) **C** = 67.1±17.7–66.9 ± 17.4 ($p = 0.922$)	Using interactive telematics appointments to treat individuals with T1DM and poor metabolic control is a successful approach that saves a lot of time, especially for patients, while yielding results that are on par with in-person appointments in terms of improved knowledge acquisition, glycaemic control, and self-care adherence to treatment.

Table 4 (continued)

Author	Aim	Setting	Sample size	Age	Study design	Digital intervention	Intervention period	Data collection method	Outcomes	Main findings	Conclusion
Harris et al., 2015 (190)	This study compared the relative effectiveness of two delivery methods for behavioural family systems therapy for diabetes (BFST-D) in face-to-face clinic settings and online videoconferencing settings using Skype to enhance adherence and glycaemic control within adolescents having T1DM who exhibit suboptimal glycaemic control.	**USA**	90	Skype = 14.94(1.77) Clinic = 15.04(1.79) years	RCT	Behavioural Family Systems Therapy for Diabetes (BFST-D) via the Clinic or Skype condition	12-week period	• **DSMP** = Diabetes Self-Management Profile (DSMP) • **HbA1c**	Adherence improved	**Hba1C** Skype = 11.15(1.73)—10.40(1.66)—10.61(1.83) Clinic = 55.55 (12.81)–10.45 (2.05)–10.31 (1.95) **P-DSMP** Skype = 48.12 (13.55)–52.84 (13.49)–50.09 (12.91) Clinic = 46.01 (12.05)–53.61 (11.83)–51.83 (11.88) **Y-DSMP** Skype = 52.64 (11.59)–56.10 (13.30)–55.55 (12.81) Clinic = 51.81 (11.53)–58.07 (8.25)–57.66 (9.50)	These results demonstrate that BFST-D can be effective when delivered through conventional methods (i.e., Clinic) or Internet-based videoconferencing (i.e., Skype). To address no adherence and inadequate glycaemic control in youths with type 1 diabetes, the administration of BFST-D through Internet-based videoconferencing is a feasible approach. This might lower significant obstacles to treatment for youth and families.

Table 4 (continued)

Author	Aim	Setting	Sample size	Age	Study design	Digital intervention	Intervention period	Data collection method	Outcomes	Main findings	Conclusion
Nunn et al., 2006 (191)	This research study intends to determine whether routine phone calls from a paediatric diabetes educator to young children with T1DM optimise hospital admissions, haemoglobin A1c (HbA1c) levels, diabetes awareness, adherence, and mental health	**New-castle, Australia**	123	Phone = 11.9 (3.7) Control = 11.9(3.0)	RCT	Bimonthly scheduled telephone calls by a pediatric diabetes educator	7 months	· **HbA1c** · **(mTDK)** = modified version of Test of Diabetes Knowledge · **Adherence** · **(SDQ)** = Strengths and Difficulties Questionnaire · **(ISAFF)** = Indicators of Social and Family Functioning · **McMaster Family Assessment Device** · **Arnold Parenting Scale**	Adherence didn't improve	**HbA1C** Phone 8.15(1.14) −8.85(1.29) Control = 8.32(1.01) −8.82(1.10) p = 0.24 **m-TDK self-scored** Phone = 79.1(57.4) 84.5(52.7) Control = 77.5(55.7) −82.4(55.6) p = 0.34 **MedicAlert (yes/no)** Phone = 26/34—31/29 Control = 29/34—28/35 p = 0.72 **Glucose records availability (yes/no)** Phone = 46/14—52/8 Control = 52/11—50/13 *P* = 0.37 According to the intervention group, their **interactions with the clinic** were more beneficial (*p* = 0.003). There were no subgroups with statistically significant differences found in the family function analysis.	Regular phone assistance provided every two months did not enhance a patient's HbA1c level, admission rates, diabetes awareness, psychological function, or self-management. However, patients determine it as a beneficial approach for improving medication compliance. Additional research is required to investigate the impact of increased frequency but reduced duration of assistance for patients facing particular challenges.

Table 4 (continued)

Author	Aim	Setting	Sample size	Age	Study design	Digital intervention	Intervention period	Data collection method	Outcomes	Main findings	Conclusion
Lawson et al., 2005 (192)	Impact of routine, standardised phone contact from a diabetic nurse educator (DNE) on medication compliance, metabolic control, and quality of life in teenagers with poorly managed type 1 diabetes.	**Ottawa, Canada** A tertiary care pediatric hospital in	46	13–17 years TM = 15.4±1.3 SC = 15.0±1.2	RCT	Diabetes nurse educator (DNE) based regular standardised telephone contact	6-month	• Blood glucose results • Insulin-dose adjustments • HbA1c • Glucose monitoring compliance • Diabetes Management Scale (CDMS) questionnaire • Diabetes Quality of Life Scale for Youth (DQOLY) • Family Environment Scale (FES)] • Total daily insulin dose • BMI	No outcome improved including compliance (adherence)	HbA1C 3 months TM = 9.7±0.3, SC = 9.3±0.3 6 months TM = 9.4±0.3, SC = 9.6±0.3 p-value = 0.26 Compliance with Diabetes management 3 and 6 months Testing BG ($p = 0.81$) Taking insulin ($p = 0.29$) Following Diet plan ($p = 0.02$) Keeping BG at the right level ($p = 0.19$) Fitting exercise into treatment plan ($p = 0.03$) Treating a reaction ($p = 0.24$) Remembering to do everything every day ($p = 1.00$) Regular phone contact from a DNE for six months did not immediately impact any of the outcome indicators.	Unlike adult studies, routine phone calls did not improve glycaemic control in teenagers with poorly managed T1DM right away. However, in these high-risk teenagers, the information and abilities acquired during the intervention could have had a delayed positive impact.

Table 4 (continued)

Author	Aim	Setting	Sample size	Age	Study design	Digital intervention	Intervention period	Data collection method	Outcomes	Main findings	Conclusion
Franklin et al., 2006 (193)	To assess Sweet Talk, a text-messaging support system designed to enhance self-efficacy, facilitate uptake of intensive insulin therapy and improve glycaemic control in paediatric patients with Type 1 diabetes	**Tayside, Scotland**	126	8–18 years **CIT** 12.7 (10.5–14.8) **CIT+ST** 14.1 (11.7–15.6) **IIT+ST** 12.6 (11.2–15.4)	RCT	Sweet Talk software system	12-month	• Self-reported adherence • HbA1c • Self-efficacy for diabetes score (SED) • Diabetes Knowledge Score (DKN) • Diabetes social support interview (DSSI) • Diabetic ketoacidosis (DKA) frequency • Severe hypoglycaemia frequency • Body mass index (BMI) • Health service usage frequency	Self-reported adherence improved	HbA1C CIT = 10.3 ± 1.7 CIT+ST = 10.1 ± 1.7 IIT+ST = 9.2 ± 2.2 p = 0.99 Self-efficacy for diabetes scale CIT = 56.0 ± 13.7 CIT+ST = 62.1 ± 6.6 IIT+ST = 63.1 ± 7.2 p = 0.003 DSSI (Insulin) CIT = 2.0 ± 1.1 CIT+ST = 4.3 ± 5.4 IIT+ST = 6.4 ± 5.8 p = 0.11 DSSI (Blood-glucose testing) CIT = 1.3 ± 1.3 CIT+ST = 6.0 ± 5.6 IIT+ST = 7.0 ± 4.9 p= < 0.001 DSSI(Diet) CIT = 1.9 ± 1.1 CIT+ST = 8.1 ± 5.6 IIT+ST = 4.4 ± 4.5 p= < 0.001 DSSI Exercise CIT = 0.6 ± 1.0 CIT+ST = 5.0 ± 4.8 IIT+ST = 3.3 ± 4.7 p= < 0.001 In a survey, 82% of patients indicated Sweet Talk has helped them better control their diabetes, and 90% indicated they would want to keep getting messages.	Sweet Talk engaged a demographic of young people that is often hard to reach and has been associated with increased self-efficacy and attention towards T1DM management. Although Sweet Talk alone did not lead to better glycaemic control, it could have helped to facilitate the start of intense insulin treatment. Thus, an innovative way to help diabetic adolescents manage their diabetic condition is through scheduled, customised SMS messages, which might also be used for chronic illnesses and other healthcare environments.

Table 4 (continued)

Author	Aim	Setting	Sample size	Age	Study design	Digital intervention	Intervention period	Data collection method	Outcomes	Main findings	Conclusion
Gomez-Peralta et al., 2023 (194)	To assess the efficacy of the insulin pen cap Insulclock on improving glycaemic control, treatment adherence, and user satisfaction in people with type 1 diabetes.	**Spain**	55	40.9 years	RCT	insulin pen cap "Insulclock"	4-week run-in phase 6-week double-arm phase	• Time in range (TIR) • Glucose management indicator (GMI) • Time above range (TAR) • Time below range • Mean amplitude of glycaemic excursions • SD • Coefficient of variation • High blood glucose index (HGBI) • Low blood glucose index	Adherence improved	**Time in range (TIR)** Active group = 5.2%; $p = 0.016$ Masked group = −0.8%; $p = 0.016$ The active group had a greater decrease in **average glucose levels**, **time spent** over the **desired range**, **glucose control indicator**, and **high blood glucose index.** The participants in the active group had a **rise in on-time insulin dosages**, whereas the masked group experienced a reduction. The active group's overall amount of insulin injections increased by 13.9% as a consequence of using Insulclock's capabilities, mostly because more doses were taken on time (13.5%)	The use of the Insulclock system was linked to enhanced regulation of blood sugar levels, reduced fluctuations in blood sugar levels, decreased risk of high blood sugar levels, and greater adherence to diabetes medication in individuals with unmanaged type 1 diabetes.

Table 4 (continued)

Author	Aim	Setting	Sample size	Age	Study design	Digital intervention	Intervention period	Data collection method	Outcomes	Main findings	Conclusion
Kaushal et al., 2022 (195)	To evaluate the effects of a text messaging-based digital health intervention with monetary incentives on self-care practices and HbA1c.	**Philadelphia (USA)**	166	12–18 years I = 15.8 (1.9) C = 15.5 (2.3)	RCT	MyDiaText™, a text messaging (TM) education and support application	6 Months	• Self-care inventory (SCI) • HbA1c measurements	Adherence improved	**Self-care inventory (SCI)** In the per-protocol analysis, the results showed a statistically significant variation in the rise in SCI scores between the groups receiving one TM per day and the control group when baseline characteristics were taken into account ($p = 0.035$). **HbA1C** No discernible change in HbA1c across the groups ($p = 0.786$).	While glycaemic control did not change from controls, a TM intervention with monetary incentives for teenagers with T1DM in poor control was linked to an increase in self-care reports. The results demonstrated sustained involvement in and the possibility of enhancing self-care through the use of this intervention. It has shown that TM is a potential approach to include teenagers with T1D and inadequate control in their self-care, and it warrants further examination. There is still a need to create a digital health intervention that has a substantial effect on glycaemic management in this particular population.

125 records through Google Scholar. 436 duplicates were removed, and 4982 titles and abstracts were screened. 4864 studies were excluded because of other types of diabetes, other diseases or they were not related to this study. The differences due to conflicts were discussed until an agreement was reached. Out of the 113 articles that had been included in the full text screening, 101 were excluded due to wrong population ($n=13$), wrong outcome ($n=89$) and wrong study design ($n=4$). From all 5418 records (5293 from the databases and 125 from Google Scholar), 12 studies were included in the systematic review.

Study risk of bias assessment

The risk of bias for the studies included in this systematic review was evaluated using the Cochrane Risk of Bias tool (ROB2) to consider different biases including, random sequence generation, allocation concealment, blinding of participants and personnel, blinding of outcome assessment, incomplete outcome data, selective reporting, and other biases [46]. This tool produces results classified as overall 'high', 'medium' or 'low' risk of bias [47].

Results

Study quality

Risk of bias in studies

The overall assessment showed that most studies demonstrated a low risk of bias in most domains, though certain concerns were identified, particularly regarding blinding (Figs. 2 and 3). **Selection Bias (Random Sequence Generation)**: All studies, except one [48], demonstrated low risk of bias in random sequence generation, as most of them provided adequate descriptions of their randomization processes. This ensured that participants were randomly assigned to intervention and control groups, minimizing selection bias. **Selection Bias (Allocation Concealment)**: Most studies provided clear descriptions of allocation concealment, ensuring that the allocation process was not revealed prior to assignment. This step was essential to prevent selection bias, and studies, including Franklin et al. [49] and Banu et al. [50], demonstrated robust procedures in place. Three studies had insufficient details regarding allocation concealment, resulting in an unclear risk of bias [51–53].

Performance Bias (Blinding of Participants and Personnel) relating to the issues of blinding of participants as well as personnel, is another aspect that has also been shown to have uniformly low risk across all the studies, which implies good blinding practices that help prevent any behavioural differences between various groups because of knowledge of the intervention. Detection bias, which investigates the blinding of outcome assessors, falls into the low risk for two studies [54, 55], while the remaining ten had unclear risk because the authors failed to report adequately on the blinding procedures employed. Blinding participants and personnel in studies involving digital interventions was not feasible due to the nature of the interventions. As a result, none of the studies fully blinded participants and personnel, but this was deemed a low risk of bias across the studies. The inability to blind in this domain was expected and did not significantly affect the internal validity of the studies because the nature of the interventions (mobile app usage) was self-evident to participants and healthcare providers. Detection Bias (Blinding of Outcome Assessment): Unlike performance bias, it was possible to blind the outcome assessors in these studies, yet many studies did not explicitly report whether they had implemented blinding in this domain. The lack of clarity in reporting whether assessors were blinded resulted in an unclear risk of bias in several studies, however two studies [54, 55] have clearly mentioned that assessors were blinded. This potential for detection bias could introduce subjectivity into the measurement of outcomes, particularly when assessors are aware of the intervention status of participants. Attrition Bias (Incomplete Outcome Data) was generally well controlled with all studies receiving a low risk of attrition bias. Studies reported minimal dropout rates, and when dropout occurred, reasons were explained, and appropriate statistical methods (such as intention-to-treat analysis) were employed to account for missing data. Therefore, incomplete outcome data posed a low risk of bias in most of the studies reviewed. Selective Reporting (Reporting Bias): No major issues of selective reporting were identified across the included studies. Most studies followed their pre-registered protocols and reported all predetermined outcomes. Selective reporting bias was therefore assessed as low risk across the board. Other potential sources of bias, such as conflicts of interest or funding source biases, were also considered. Most studies disclosed their funding sources, and no substantial evidence suggested that funding influenced the outcomes. As a result, the "other biases" category was largely classified as low risk across the included studies.

Thus, most studies displayed a low risk of bias in key domains such as random sequence generation, allocation concealment, incomplete outcome data, and selective reporting (as illustrated in Fig. 2). However, the inability to blind participants and personnel was inevitable due to the nature of the interventions but was considered low risk. The primary concern across several studies was the lack of clarity regarding blinding of outcome assessment, leading to an unclear risk of detection bias. One study, Rafeezadeh et al. [48] stood out with a high risk of bias in random sequence generation, which may limit the generalizability of its findings. Overall, the included studies demonstrated methodological rigor, though improvements in the reporting of blinding procedures for

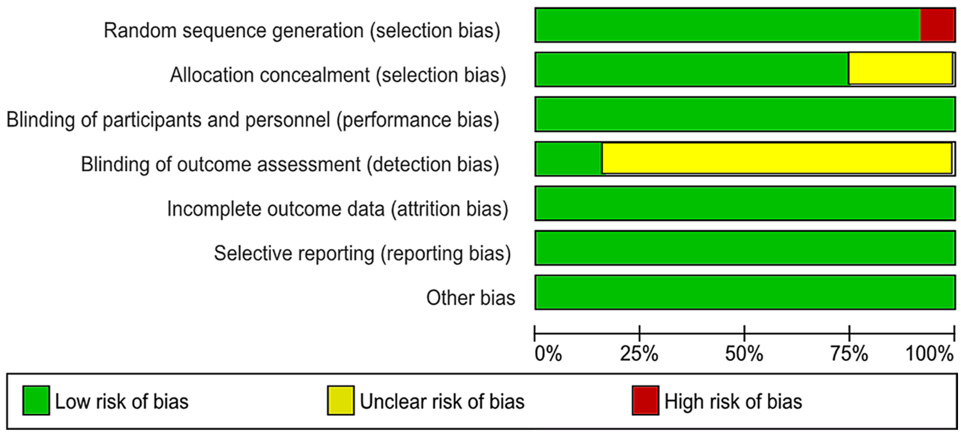

Fig. 2 Risk of bias graph

outcome assessment would further enhance their quality. The findings of this assessment tool support the statement that most of the studies have negligible risk in all the categories. Notably, one research, by Rafeezadeh et al. [48] has had repercussions in random sequence generation as a sign of high risk of bias limiting the study's methodological credibility. This case should be considered in reviewing the synthesis of the proposed line of work as this is an outlier that has implications for the reliability of the review's conclusions. All other reviewed literature has also depicted a very low risk of bias in most domains which in turn boosts the credibility of the evidence towards improvement of adherence to T1DM by digital health solutions.

Study characteristics

The systematic review entailed the selection of 12 papers out of the 4903 articles searched from the five databases and google scholar through a rigorous eligibility check. This work has been published till 2025 and indicates the rising focus and commitment to developing digital health solutions for T1DM. Most of the studies examined the impact of digital intervention on adherence to the management of T1DM either as the primary or secondary measure. All papers included in the evaluation met the requirements of being randomised control trials. Each research assessed different types of digital health interventions such as Web-based, m-health and e-health interventions. These digital health interventions encompassed mobile applications for supporting diabetes self-management, telemedicine for remote consultation and adherence improvement, and online patient education platforms to increase patients' knowledge and self-care capacities. The studies were conducted in several countries: two studies each were conducted in Philadelphia USA [53, 56], and Spain [52, 57]; one study each was conducted in Iran [48], Bangladesh [50], Northern Greece [58], Italy [59], Australia [54], Canada [55], and Scotland [49]. While one study did not mention the details regarding the settings in which it was conducted [51].

There were approximately 2169 individuals (mostly adolescents) across all 12 studies. The sample size of the studies also varied from 46 participants to several hundred participants in some studies such as 990, proving that the range of research domains is vast and includes both small-scale individual experiments and large multicentre trials. The included studies specifically focused on a group of people diagnosed with T1DM. The studies focused on children, adolescents and adults with an age range from 4 to 45 years. One study has a minimum value of 8 years [49] while another study has a maximum value of more than 48 years [50]. The duration of the studies ranged from 3 months to 1 year and 5 months.

The main variables that have been evaluated in those studies were patients' adherence to diabetes management guidelines, changes in glycaemic control as reflected by HbA1c level, knowledge and awareness about DM, self-efficacy, satisfaction, and quality of life. Other patient outcomes assessed in several of these trials encompassed various blood markers such as Fasting Blood Glucose (FBG), and pre- and post-prandial blood glucose test. Additionally, insulin levels, insulin adjustments, physical activity, body mass index (BMI), hypoglycaemic and hyperglycaemic events, primary care visits, readiness to exchange information, communication and interaction with healthcare professionals, engagement, rates of rehospitalization, health-related quality of life and costs were also evaluated in some studies.

Based on the evidence gathered from the studies under review, the following are the summarised findings which shed light on different facets of the role and impact of digital health interventions on patient's adherence to T1DM management guidelines.

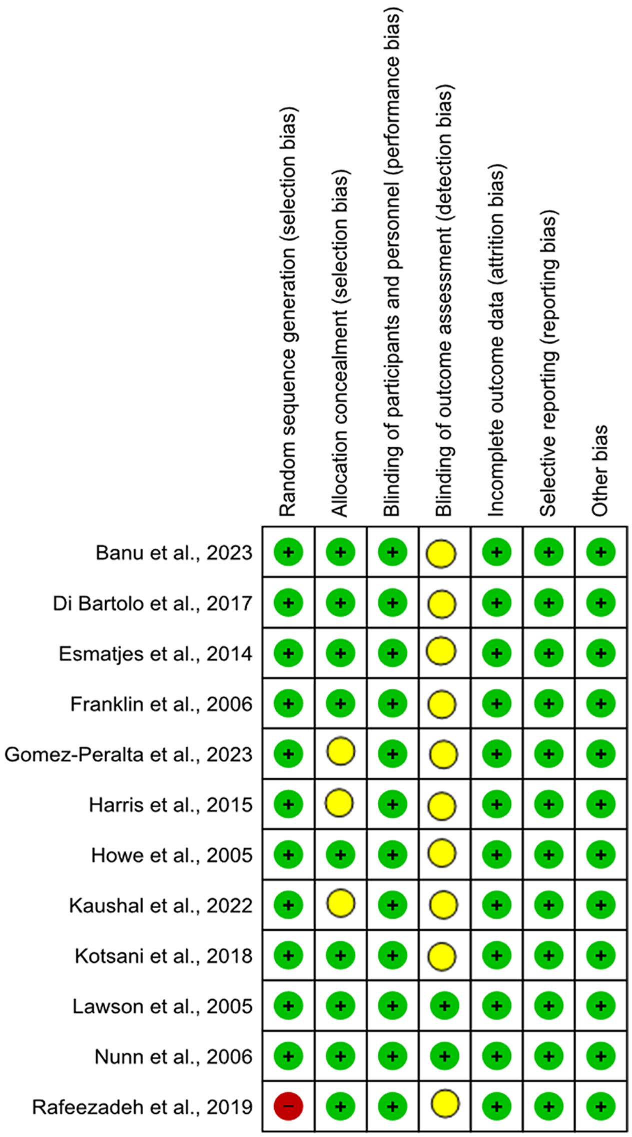

Fig. 3 Risk of bias summary

Digital health intervention types in the included studies

Several forms of digital health interventions were observed in the included studies, all of which were developed to improve various aspects of T1DM management. Different types of interventions were web and mobile application-based, telephones and telemedicine, and internet-based education. Most research centred around web-based software and mobile applications that could be used to support diabetes self-management, such as M-Health Education (MHE) [50], IBGstar [59], Sweet Talk software system [49], and text messaging-based education and support application "MyDiaText™" [53]. These apps offered abilities including real-time monitoring of glucose levels, records of the amount of insulin required, food and carbohydrate counters, and notifications for the medicine's intake and blood glucose recording. For instance, in the study by Banu et al. [50], the MHE group demonstrated substantial ($p<0.01$) improvements in knowledge, adherence to self-management, and health outcomes as compared to the control group as well as the traditional health education (THE) group. The MHE group considerably outperformed the THE group in terms of improvement in knowledge about food, physical activity, follow-up visits and blood glucose tests, quitting smoking, and fundamental and technical understanding of DM. The iBGStar multicentre RCT showed no between-group difference at 6 months ($p=0.51$). (187). The study conducted by Rafeezadeh et al. [48] explored the effectiveness of a designed interactive video game-based intervention for T1DM self-care adherence. It was observed that the self-care score of the intervention group (82.9±7.8) was found to be substantially higher than the control group (77.3±7.7)), however, this difference was not statistically significant ($p=0.57$). In contrast, HbA1c reduction was statistically significant ($p=0.027$). 5 out of 12 studies were based on different forms of telemedicine intervention such as telenursing services [58], two face-to-face and five telematic-based interventions [57], Education and telephone case management (ED + TCM) [56], Behavioral Family Systems Therapy for Diabetes (BFST-D) through the Clinic or Skype condition [51], and scheduled telephone calls [54, 55]. These telemedicine solutions imply that patients avail themselves of healthcare services through distance communications with practitioners. These services ensured that follow-up and advice delivery was more frequent and patient-specific thus enhancing patients' adherence. These studies revealed that patients receiving telemedicine services isolated from their physicians could have continuous communication, get timely support, and thus, adhere to the treatment regimens. One study explored the effect of CGM-based tools [52] because CGM supplies real-time, constant glucose detection. These systems assisted the patients in modifying their insulin regimens at the right time, which in turn decreased average glucose levels but also assisted in reducing hyperglycaemic and hypoglycaemic episodes. It was observed that CGM was associated with better glycaemic control since HbA1c levels were lower and the number of severe hypoglycemic events was decreased. Moreover, Gomez-Peralta et al. [52] highlighted that the use of the Insulclock system was linked to enhanced regulation of blood sugar levels, reduced fluctuations in blood sugar levels, decreased risk of high blood sugar levels, and greater adherence to diabetes medication in individuals with unmanaged T1DM.

Effects of digital health interventions on clinical outcomes

Among all identified measures, the overall positive impact of digital health interventions on the glycaemic levels of patients was one of the major outcomes of digital health intervention. Whereas the most assessed clinical outcome for evaluating the glycaemic control in patients in the included RCTs was HbA1c. The results of the reviewed studies provided emerging evidence of the positive impact of various digital health interventions on HbA1c levels. Improvements in HbA1c levels were consistently reported across various interventions. Moreover, another trial assessing adherence to glycaemic management and glucose self-monitoring before and after using telenursing reinforcement in patients with T1DM indicates a considerable decrease in HbA1c levels throughout the intervention period (8.3 ± 0.6% at study start vs. 7.8 ± 1% at study end, p-value = 0.03) [59]. These clinical outcomes suggest that digital health solutions can play a critical role in optimising diabetes management and reducing complications associated with T1DM. Further, studies involving mobile phone messaging systems indicated that patients experienced significant reductions in both hyperglycaemic and hypoglycaemic events, contributing to overall better glycaemic control [49]. For instance, a large-scale trial showed that patients receiving Mobile Health Education (MHE) significantly improved their blood glucose level as compared to patients receiving Traditional Health Education (THE) after the intervention over a year, with a difference of 0.31 and statistical significance of $p < 0.01$ [50]. Along with this, a notable decrease in postprandial blood glucose levels, HbA1c levels, occurrences of simple hypoglycaemic episodes, and the frequency of monitoring blood glucose levels were observed in the intervention group. Moreover, one study reported on digital tools based on CGM [52]. This study was based on the insulin pen cap "Insulclock" which also showed effective outcomes in improving glycaemic control by providing support to enhance adherence to diabetes medication in individuals with unmanaged T1DM.

Effects of digital health interventions on patient-related outcomes

Studies indicated that several patient-related outcomes such as improved quality of life and satisfaction with care were improved because of digital health interventions [54, 56]. Most of the researched articles showed that there was high satisfaction from users because of the flexibility, accessibility, and customisation offered by digital solutions. Telemedicine services especially highlighted the increased and positive patient interaction which added to the patients' support and motivation. For instance, a study highlighted that patient who engaged in telemedicine received more support from their physicians, thus, adhering more to treatment plans and being more satisfied with the care provided [58]. Moreover, patient education through information and communication technology tools consisting of individualised information and interactive lessons helped the patients gain better knowledge and self-confidence in the management of their conditions and improve their quality of life [50, 56]. It was also observed that websites and other technological tools-based healthcare interventions provide personalised information and educational sessions focusing on diabetes [54]. These platforms sought to enhance the levels of knowledge and self-competence among patients to enhance how they could handle their diagnosis. Research showed that these subjects had increased levels of understanding about diabetes and perceived compliance with guidelines concerning its management [48].

Effects of digital health interventions on health behaviour

Digital health interventions also positively affected the behaviour regarding adherence to protocol among diabetic patients. Features like real-time feedback, health alerts, and other related support like self-monitoring prompts were considered to play a significant role in maintaining consistent self-management behaviours among users of the mobile applications [53]. For instance, a study on Sweet Talk [49], a mobile-based message intervention, revealed that improvements were observed in self-reported adherence ($p = 0.04$), diabetes social support ($p < 0.001$), and diabetes self-efficacy ($p = 0.003$) in both groups receiving Sweet Talk assistance while showed no significant HbA1c difference between groups ($p = 0.99$). Further, Banu et al. 's [50] study also emphasised that mobile-based education interventions enhance the management of T1DM by increasing diabetes knowledge and adherence to self-management as well as health outcomes (p-value < 0.01). It was also observed that the adoption of a mobile health education (MHE) group can lead to improvement in knowledge about food, physical activity, follow-up visits and blood glucose tests, quitting smoking, and fundamental and technical understanding of diabetes [50]. These changes in health behaviour were important to allow for attaining and sustaining suitable glycaemic goals. Moreover, the studies pointed out that telemedicine-based educational models that improved the understanding of the disease and the patient's condition promoted better diet, physical activity and medication compliance [53, 59]. Another research found that the education and telephone case management-based interventions improved adherence to T1DM management. When comparing the intervention group's estimation of their blood glucose levels to the standard care group, they found a substantial increase in adherence [56]. Another study highlighted the effectiveness of education on blood glucose signalling self-awareness, and the participants reported learning more about the information about normal, hyperglycaemic, and hypoglycaemic blood glucose levels and their management [54].

Table 5 Tool used and adherence measures (medication, monitoring, diet, physical activity)

Study	Tool Used	Medication	Monitoring	Diet	Physical Activity
Rafeezadeh et al., 2019	SCI	✔	✔	✔	✔
Kotsani et al., 2018	DSMP	✔	✔	✔	✔
Franklin et al., 2006 (Sweet Talk)	SMBG frequency + SMS	✔	✔	✖	✖
Esmatjes et al., 2014 (iBGStar)	SMBG frequency	✖	✔	✖	✖
Gomez-Peralta et al., 2023 (Insulclock)	Insulin timing	✔	✖	✖	✖
Harris et al., 2015	Dietary logs + SMBG	✖	✔	✔	✖
Banu et al., 2023	DSMP short form	✔	✔	✔	✔
Di Bartolo et al., 2017	Lifestyle checklist	✖	✖	✔	✔
Kaushal et al., 2022	Insulin diary + SMBG	✔	✔	✖	✖

Discussion

This systematic review aimed to assess the role and efficacy of digital health solutions in helping patients with T1DM adhere to their treatment plans. Thus, the goal of this study was to determine how digital health technology enhances T1DM patient adherence to treatment, glycaemic control and other associated outcomes. For this purpose, the data from approximately 2169 participants in 12 RCTs were thoroughly reviewed and analysed. The findings from these studies demonstrated Digital Health Interventions have the potential to assist people with T1DM in effectively adhering to T1DM management and achieving better glycaemic control. In patients with T1DM, this was accomplished by successfully lowering HbA1c values and improving glycaemic control, adherence to diabetic management and self-management. The type of study settings, research methodology, participant count, and digital health characteristics and functions varied between the studies. But all studies indicated the effectiveness of digital health solutions in improving the adherence of patients to treatment of diabetes. The improvements in HbA1c as seen in this review for individuals with T1DM are in line with findings from prior studies [18, 40, 60, 61]. We grouped adherence measures into four domains: medication, monitoring, diet, and physical activity (Table 5). Most studies assessed monitoring adherence (SMBG/CGM frequency), with fewer addressing diet or activity. Broad tools like SCI and DSMP covered multiple domains, whereas technology-specific tools (e.g., Insulclock) focused only on medication timing. This heterogeneity highlights the need for standardised adherence measures in future research.

It was observed that digital health interventions are effective in improving the clinicians' and patients' outcomes related to T1DM management. The evidence from randomized controlled trials showed that digital health technologies such as m-health and e-health, digital tools, telemedicine, and CGM-based digital systems could enhance glycaemic control. These findings are in line with other studies where real-time data monitoring equipment of the emergent CGM systems and mobile apps facilitated accurate and timely modification of diabetes self-management [62–64]. The findings indicate the role of such interventions in the effective reduction of severe hypoglycaemia or hyperglycaemic events implying that the application of digital interventions makes diabetes management safer in both the short term and the long term. Most of the included trials showed a decrease in HbA1c levels in the intervention group. Variable improvements in other patient outcomes, such as blood pressure, body weight, fasting blood glucose, hypo- and hyperglycaemic events, adherence to medication and self-care were also observed in several trials. Many of these clinical outcomes have been the subject of other research [34, 40, 52, 65] nevertheless, in contrast to HbA1c, no consistent clinical effect has been found.

The findings of this review also indicated that implementation of digital health interventions can yield effective patient-related outcomes such as improved quality of life, adequate patient engagement and satisfaction, good communication between healthcare professionals and patients, improved adherence to guidelines and increased knowledge and awareness regarding T1DM. Higher patient engagement combined with satisfaction efficiency notably in systematic communication like telemedicine were discussed as one of the frequent findings in the studies. The perceived improvements in patients' quality of life through mobile applications, CGM-based systems and telemedicine interventions also indicate the psychological and emotional impact of these technologies.

The reviewed studies also highlighted the effectiveness of digital technology-targeted interventions in enhancing the aspect of self-management and health behaviour among T1DM patients. This finding implies that the educational factors of the mobile applications and web-based platforms were useful mainly in enhancing knowledge and self-care management among T1DM patients. Thus, these tools can have a positive effect on the likelihood of compliance with prescribed regimens because of the possibility of direct communication with the patient and the tool's specific characteristics. These results are also in line with the behavioural change theories which highlight the significance of education, perceived self-ability and continuous feedback in adopting good health behaviour [66]. Most of the implemented digital health technologies for T1DM management also provide constant feedback in addition to constant monitoring, thus establishing patients' behaviour modification and enabling them to make the right choices and respond required. The age-stratified findings suggest that adolescents engage with interventions utilizing SMS-based or gamified approaches (e.g., Sweet Talk), whereas adults benefit from device-based interventions, such as continuous glucose monitoring (CGM) integration or telehealth platforms. These outcomes suggest that tailoring digital diabetes management tools to specific age groups may optimize their effectiveness, underscoring the importance of age-sensitive design.

One significant limitation of this review study is that studies other than RCT were not included. According to authorities like the National Institute for Health and Care Excellence [67], observational research and non-randomised trials may provide valuable insights into the efficacy of digital health interventions. However, non-randomised trial designs are excluded from these studies as they are more susceptible to a variety of known and undiscovered biases [68]. Another possible limitation of the review process might have been its exclusive focus on English-language material that was accessible throughout the search. Even though the data were evaluated thoroughly by the reviewer, it is possible that certain articles that may have been pertinent can be excluded [69]. It was discovered that many of the main studies had poor reporting standards and poor methodological quality, which was often caused by blinding, concealing, and randomisation between individuals and evaluators. Nevertheless, it should be noted that since participants in digital health-based RCTs may need help to utilise digital health technology, randomisation, deception, and blinding between patients and researchers may be difficult.

Conclusion

This systematic review offered a thorough assessment of the role and effectiveness of digital health interventions for adherence to T1DM management. It was observed that digital health interventions had beneficial impacts on relevant clinical and patient-related outcomes in addition to the desired health behaviours. The findings suggest that digital health treatments may enhance glycaemic control by optimising HbA1c, adherence to medication, quality of life and overall well-being. Therefore, based on the findings of this review, it can be ascertained that digital health technologies enhance adherence to management regimens in T1DM and consequently, clinical and patient-related outcomes. Future studies should aim to continue identifying the efficiency of long-term use of the digital tools and patient engagement with the technology. In doing so, the healthcare community can derive the maximum benefit from these innovations, to improve the care of T1DM and quality of life of patients with this chronic disease.

Abbreviations

DM	Diabetes Mellitus
IDF	International Diabetes Foundation
T1DM	Type 1 Diabetes Mellitus
HbA1C	Glycated Haemoglobin A1c
ADA	American Diabetes Association
EASD	European Association for the study of Diabetes
RCT	Randomised control trials
ICT	Information and communication technologies
d-health	Digital health
m-health	Mobile health
e-health	Electronic health
DSMES	Diabetes self-management education and support
PRISMA	Preferred reporting items for systematic reviews and metanalysis
PROSPERO	International Prospective Register of Systematic Reviews.
PICOP	Population/Problem
I	Intervention
C	Comparison
O	Outcome
ROB2	Risk of bias tool
MHE	M-health education
THE	Traditional health education
ED+TCM	Education and telephone case management
BFST-D	Behavioural family systems therapy for diabetes
CGM	Continuous Glucose Monitoring systems

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Author contributions
All authors contributed to the overall study design and development. Mohammad Jawad (MJ) and Saima Afaq (SA) conceptualized the study. MJ, SA, Sana Hussain (SH), and Asif Rehman (AR) contributed to the methodology design. MJ, SH, and AR conducted the literature search, screened studies, and performed data analysis along with Zia ul Haq (ZH) and Arshad Hussain (AH). MJ drafted the initial manuscript. Saima Afaq (SA), Syeda Fatima Jamal (SFJ), and Samrina Khan (SK) provided critical review and revisions of the manuscript. Zia Ul Haq (ZH) and Arshad Hussain (AH), along with SA, provided supervisory oversight and expert guidance throughout the review process. Moath Ahmed Abdullah Almuradi (MAAA) contributed to reviewing the methodology and editing the manuscript. All authors reviewed and approved the final version of the manuscript. All authors reviewed and approved the final version of the manuscript.

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Data availability
All data analysed during this systematic review are included in the article. The search strategy, study selection process, and data extraction details are described in the manuscript.

Declarations

Ethics approval and consent to participate
Not applicable. This systematic review does not involve primary data collection.

Consent for publication
Not applicable. This systematic review does not contain individual person's data.

Competing interests
The authors declare no competing interests.

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