Review

Digital Health Interventions to Prevent Type 2 Diabetes Mellitus: Systematic Review

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Abstract

Background: Digital health interventions (DHIs) have rapidly evolved and significantly revolutionized the health care system. The quadruple aims of health care (improving population health, enhancing consumer experience, enhancing health care provider [HCP] experience, and decreasing health costs) serve as a strategic guiding framework for DHIs. It is unknown how DHIs can impact the burden of type 2 diabetes mellitus (T2DM), as measured by the quadruple aims.

Objective: This study aimed to systematically review the effects of DHIs on improving the burden of T2DM, as measured by the quadruple aims.

Methods: PubMed, Embase, CINAHL, and Web of Science were searched for studies published from January 2014 to March 2024. Primary outcomes were the development of T2DM, hemoglobin A_{1c} (HbA_{1c}) change, and blood glucose change (dysglycemia changes). Secondary outcomes were consumer experience, HCP experience, and health care costs. Outcomes were mapped to the quadruple aims. DHIs were categorized using the World Health Organization's DHI classification. For each study, DHI categories were assessed for their effects on each outcome, categorizing the effects as positive, negative, or neutral. The overall effects of each DHI category were determined by synthesizing all reported positive, neutral, or negative effects regardless of the number of studies supporting each effect. The Cochrane risk-of-bias version 2 (RoB 2) tool for randomized trials was used to assess the quality of randomized controlled trials (RCTs), while the ROBINS-I (risk of bias in nonrandomized studies of interventions) tool was applied for nonrandomized studies.

Results: In total, 53 papers were included. For the T2DM development outcome, the effects of DHIs were positive in 1 (1.9%) study and neutral in 9 (17%) studies, and there were insufficient data to assess in 4 (7.5%) studies. For the dysglycemia outcome, the effects were positive in 23 (43.4%) studies and neutral in 24 (45.3%) studies, and there were insufficient data in 6 (11.3%) studies. There were mixed effects on consumer experience (n=13, 24.5%) and a lack of studies reporting HCP experience (n=1, 1.9%) and health care costs (n=3, 5.7%). All studies that reported positive population health outcomes used a minimum of 2 distinct categories of DHIs. Among these successful studies, the one that reported delaying the development of T2DM and 16 (69.6%) of those reporting improvements in dysglycemia involved HCP interaction. Targeted communication with persons (TCP), personal health tracking (PHT), and telemedicine (TM) showed some evidence as a potentially useful tool for T2DM prevention and dysglycemia.

Conclusions: The effects of DHIs on T2DM prevention, as measured by the quadruple aims, have not been comprehensively assessed, with proven benefits for population health, mixed results for consumer experience, and insufficient studies on HCP experience and health care costs. To maximize their effectiveness in preventing T2DM and managing dysglycemia, DHIs should be used in combination and strategically integrated with in-person or remote HCP interaction.

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KEYWORDS

digital health; type 2 diabetes; prediabetes; prevent; digital health intervention; PRISMA

Introduction

Type 2 diabetes mellitus (T2DM) is a growing health problem worldwide that affects all income levels and puts a heavy burden on health care systems [1]. The increased prevalence of T2DM is largely due to changes in diet, rising obesity rates, and decreased physical activity [2]. Therefore, improving lifestyle can potentially help prevent T2DM [1]. Diabetes prevention programs (DPPs) and other lifestyle modifications strategies have been applied worldwide, demonstrating that such changes can effectively reduce the risk of developing T2DM [2-6].

Digital health interventions (DHIs), the application of digital technologies in health care [7], have transformed how health care is provided and experienced, leading to great health system efficiencies and clinical benefits [7-9]. Given the diverse communities involved in DHI (ie, technologists, researchers, clinicians, consumers, and government stakeholders), there is a need to establish a common language among these groups [7]. To address this need, the World Health Organization (WHO) developed a DHI classification system to provide a shared framework for naming, grouping, and evaluating DHIs. According to this classification, each DHI is categorized into groups based on primary users: persons, health care providers (HCPs), health system managers, and data services [7].

DHIs have been extensively applied in chronic disease management, showing clinical outcome improvements, better management, and cost savings [10-15]. During the past 10 years, DHIs are being increasingly applied in T2DM prevention, such as text messaging, web-based systems, telemedicine (TM), mobile health, software, wearables, and artificial intelligence (AI) [16,17]. A systematic review by Van Rhoon et al [18] in 2020 demonstrated that DHIs significantly reduce weight, enhance dysglycemia, and decrease T2DM incidence. According to the systematic review by Nguyen et al [19] in 2024, DHIs show further enhanced efficacy in preventing T2DM, highlighting the success of computer-based and mobile health in weight reduction, hemoglobin A_{1c} (HbA_{1c}) improvement, and T2DM incidence reduction.

The quadruple aims of health care are the overarching goals focusing on improving population health, enhancing consumer experience, improving HCP experience, and decreasing health costs [20]. The quadruple aims have been regarded as a strategic compass in guiding DHIs in different contexts, such as chronic disease prevention [21], diagnosis and treatment [22,23], health care delivery [24], planning or decision-making [25], and managing unique health care challenges, such as the COVID-19 pandemic [26].

The impacts of DHIs on improving the burden of T2DM, as measured by the quadruple aims, still remain largely unknown. Our aim was to systematically review the current literature to examine the effects of DHIs on reducing the burden of T2DM, as measured by the quadruple aims.

Methods

Study Design

This systematic review was conducted and reported following PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guidelines of 2020 [27]. Details of the PRISMA 2020 checklist are shown in Multimedia Appendix 1 [27]. The protocol of our systematic review was prospectively registered at PROSPERO (International Prospective Register of Systematic Reviews; registration number CRD42024512690). Minor changes were made to the registration information: the title was updated, the quadruple aims were added to the objectives, and WHO's DHI classification was included in the data synthesis.

Ethical Considerations

Our study was a systematic review that used nonidentifiable, secondary data from published studies. According to institutional policies, no ethics review was required.

Search Strategy and Selection Criteria

The PubMed, Embase, CINAHL, and Web of Science databases were searched with keywords in both Medical Subject Headings and title/abstract formats: "digital health interventions," "type 2 diabetes," and "prevention." The review included only studies conducted in the past 10 years, from January 2014 to March 2024 (due to the emerging nature of the digital transformation in health care). Building, testing, and finalizing the search approach were performed by the research team, in consultation with 2 research librarians from the University of Queensland (Multimedia Appendix 2).

Inclusion and exclusion criteria are listed in Table 1. The intervention of interest was defined as the use of DHIs in support of the prevention of T2DM in individuals with monitored blood glucose or HbA_{1c}. Given our focus on assessing the effects of DHIs on preventing or delaying the onset of T2DM, and considering that the diagnostic criteria for T2DM include HbA_{1c}, blood glucose, and clinical criteria, our primary outcomes were the development of T2DM, HbA_{1c} change, or blood glucose change (dysglycemia changes). Secondary outcomes were consumer experience, HCP experience, and health care costs. Quantitative and qualitative data were included in our review. Studies were excluded if individuals or populations had known diabetes (T2DM, type 1 diabetes, or gestational diabetes, as described by authors of specific studies) or outcomes that did not report the development of T2DM, HbA_{1c} change, or blood glucose change.

Table 1. Systematic review inclusion and exclusion criteria.

Factor	Inclusion criteria	Exclusion criteria
Population	Individuals and populations who had blood glucose or HbA_{1c}[a] monitored	People with known diabetes (T2DM[b], type 1 diabetes, or gestational diabetes)
Intervention	The use of DHI[c] in support of prevention of T2DM	Not meeting inclusion criteria
Study design	RCTs[d], non-RCTs, historically controlled studies, before-after studies, observational studies (cohort, case-control, cross-sectional studies), conference papers	Review studies, incomplete studies, full text not available
Comparator	Different DHI methods, routine care, or no comparator	No exclusions
Outcome	Primary outcomes: • Development of T2DM • HbA_{1c} change • Blood glucose change Secondary outcomes: • Consumer experience: any qualitative or quantitative measure of all interactions, influenced by an organization's culture, that shape consumer perceptions across the DHI [28]; experience with the HCP[e], consumer satisfaction, and experience with the entire DHI system [29] • HCP experience: any qualitative or quantitative measure of all interactions and perceptions of HCPs regarding DHIs, such as the work environment, organizational culture, colleagues, and consumers [30] • Health care costs: costs for consumers, organizations, or society, directly or indirectly, due to the implementation of DHIs [31]	Not reporting the development of T2DM, HbA_{1c} change, or blood glucose change
Publication year	2014-2024	N/A[f]
Language	English	Other languages

[a]HbA_{1c}: hemoglobin A_{1c}.
[b]T2DM: type 2 diabetes mellitus.
[c]DHI: digital health intervention.
[d]RCT: randomized controlled trial.
[e]HCP: health care provider.
[f]N/A: not applicable.

Study Selection Process

Five reviewers participated in the selection and data extraction processes (authors TD, WW, QO, and LW as primary reviewers and author CS as a senior reviewer). All papers retrieved from the database were collected and imported to EndNote version 20 (Clarivate) before being uploaded to Covidence version 2. Titles and abstracts of identified studies were screened twice (by TD, WW, QO, and LW) for potential eligibility using the inclusion and exclusion criteria. Full texts that met the inclusion criteria were retrieved and independently evaluated for their eligibility by the reviewers. Duplicates identified either automatically by Covidence or manually were excluded. Reasons for excluding full-text papers were reported. Any disagreements were solved via discussion and consensus.

A data extraction form was developed by the research team and uploaded to Covidence (Multimedia Appendix 3). Data from the selected papers were extracted and then checked (TD and QO). Any discordance was resolved via discussion and consensus of the reviewers.

Statistical Analysis

Primary and secondary outcomes were mapped to the quadruple aims, which included improving population health, enhancing consumer experience, enhancing HCP experience, and reducing health costs. The population health aspect was measured by the development of T2DM and dysglycemia changes (changes in HbA_{1c} or blood glucose).

Using WHO's DHI classification (2023 version) [7], DHIs were classified into different categories, such as targeted communication with persons (TCP) for targeted individuals, untargeted communication with persons for undefined groups, person-to-person communication (PPC) in networks or forums, personal health tracking (PHT) for self-monitoring, on-demand communication with persons (DCP) for accessing health information, person-centered health records (PHR), HCP decision support (DS), and TM [7]. Details of the classification are shown in Multimedia Appendix 4.

For each study, DHI categories were assessed for their effects on each outcome, categorizing the effects as positive, negative, or neutral:

- Quantitative data: Effects were reported as "positive" if there was a statistically significant improvement in outcomes, "negative" if outcomes statistically worsened, "neutral" if there was no statistically significant impact, and "not available" if data were insufficient for evaluation.
- Qualitative data (consumer experience and HCP experience outcomes): Effects were reported as "positive" if there was only positive feedback, "negative" if there was only negative feedback, "mixed" if there was both positive and negative feedback, "neutral" if there was no positive and negative feedback, and "not available" if data were insufficient for evaluation.

The overall effects of each DHI category were determined by synthesizing all reported positive, neutral, or negative effects regardless of the number of studies supporting each effect.

A meta-analysis was not performed because of the numerous heterogeneous study designs with different interventions or outcomes.

Risk-of-Bias Assessment

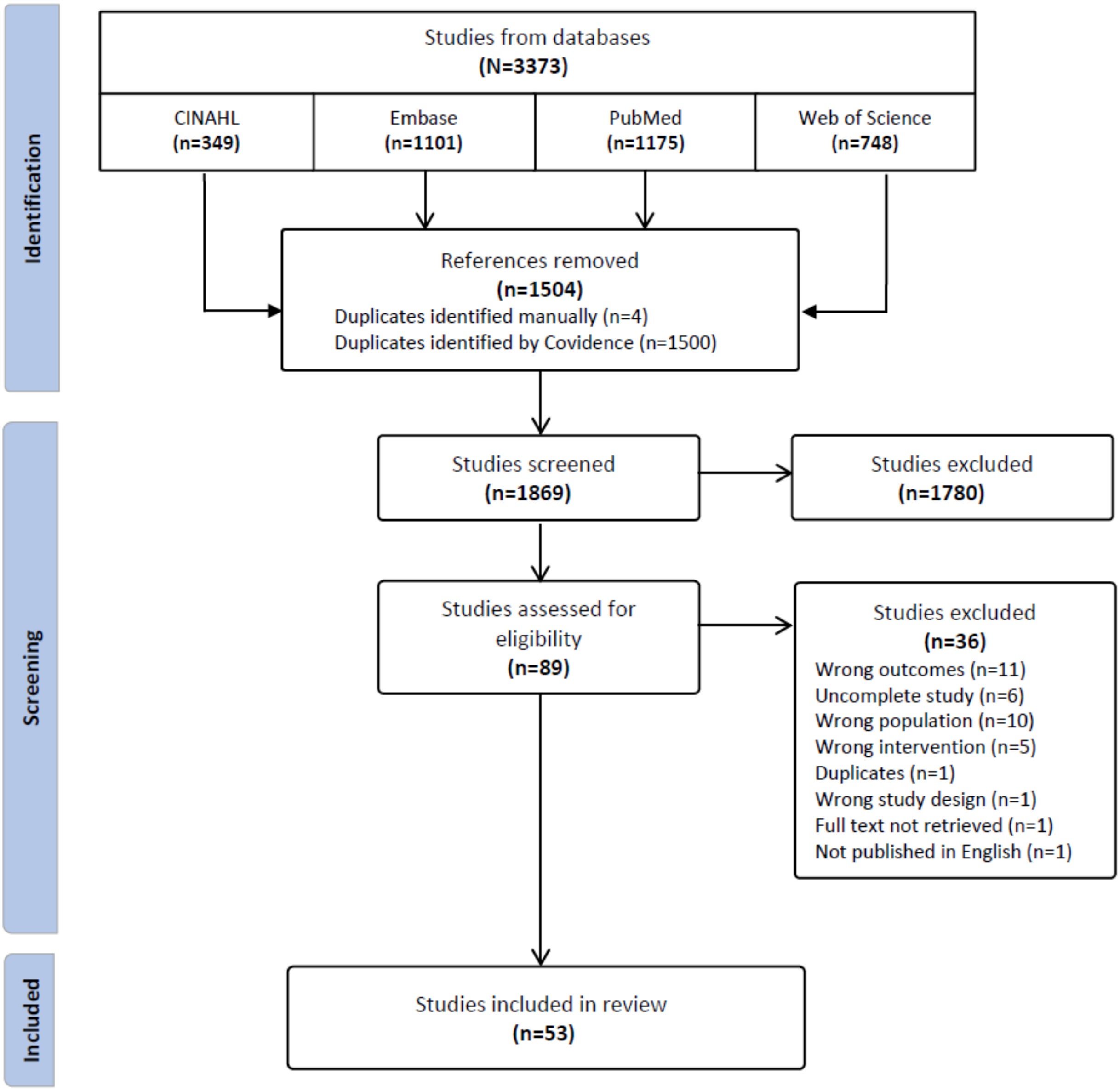
The Cochrane risk-of-bias version 2 tool (RoB 2) for randomized trials was used to assess the quality of RCTs [32], while the ROBINS-I (risk of bias in nonrandomized studies of interventions) tool was applied for nonrandomized studies [33] by TD, QO, and LJ. Any disagreements were solved via discussion and consensus.

Results

Characteristics of Included Studies

In total, 3373 citations were retrieved from the database search, of which 53 (1.6%) met the inclusion criteria, encompassing a total of 34,488 participants. The number of papers at each stage and the reasons for exclusion are detailed in Figure 1.

Figure 1. PRISMA flow diagram for study selection. PRISMA: Preferred Reporting Items for Systematic Reviews and Meta-Analyses.



The characteristics of the included studies are shown in Multimedia Appendix 5 [5,10,16,34-83]. Most studies were conducted in health care settings (n=35, 66%) and in high-income countries (n=49, 92.5%) [84]. RCTs were the most common research design (n=31, 58.5%). All studies had a duration of at least 3 months. The DHI duration fluctuated from 1 to 48 months. DHIs were mostly applied in combination with HCP interactions (n=43, 81.1%).

Risk of Bias

The nonrandomized studies showed a disproportionately high number of moderate and serious risks of bias (n=17, 77.3%), predominantly due to not accurately recording and analyzing confounders. In the RCTs, the risk of bias in population health outcomes ranged from low to high, while the risks of bias in HbA_{1c} and blood glucose change outcomes exhibited some similarities, with approximately 12 of 22 (54.5%) and 10 of 23 (43.5%) studies, respectively, presenting either some concerns or high risks. However, a few studies (n=7, 77.8%) had a high risk of bias or some concerns in the T2DM development outcome. This was mainly due to discrepancies observed in the measurement of the T2DM development outcome between groups and bias resulting from missing outcome data. There were no high risks of bias in consumer experience and health care cost outcomes, with the majority having low risks (n=37, 70%, and n=35, 66.7%, respectively). The HCP experience outcome was not assessed in RCTs. There were 24 (45.3%) studies with a low risk of bias in all outcomes and 10 (41.7%) studies with both a low risk of bias and an intervention duration of at least 1 year. Details are shown in Multimedia Appendix 6 [5,10,16,34-83].

Study Outcomes

Five outcomes were reported: consumer experience (n=13, 24.5%), health care costs (n=3, 5.7%), HCP experience (n=1, 1.9%), development of T2DM (n=14, 26.4%), and dysglycemia changes (n=52, 98.1%). Many studies reported multiple outcomes.

Study Interventions

In total, 15 DHIs were investigated. The prevalence of each DHI is visualized in Figure 2 [5,10,16,34-44,46-83,94].

Using WHO's DHI classification, 7 DHI categories were identified: TCP, PPC, PHT, DCP, PHR, HCP DS, and TM.

For the T2DM development outcome, the effects of DHIs were positive in 1 (7.1%) study and neutral in 9 (64.3%) studies, and there were insufficient data to assess in 4 (28.6%) studies. For the dysglycemia outcome, the effects were positive in 23 (43.4%) studies and neutral in 24 (45.3%) studies, and there were insufficient data in 6 (11.3%) studies. Among the 10 (18.9%) studies with a low risk of bias in all outcomes and an intervention duration of at least 1 year, none assessed the development of T2DM; the effects of DHIs on dysglycemia were positive in 7 (70%) studies and neutral in 2 (20%) studies, and there were insufficient data in 1 (10%) study.

The effects of DHIs in all studies on consumer experience were mixed, with most being positive (n=7, 53.8%). The effects of DHIs on costs, assessed in 2 (3.8%) studies, were found to be negative. The only study reporting HCP experience indicated a positive effect.

Table 2 highlights the effect of each DHI category on each outcome. The effects of DHI categories and subcategories on the outcomes in each study are illustrated in Multimedia Appendix 7 [5,10,16,34-83].

Figure 2. Distribution of DHIs across studies. DHI: digital health intervention.

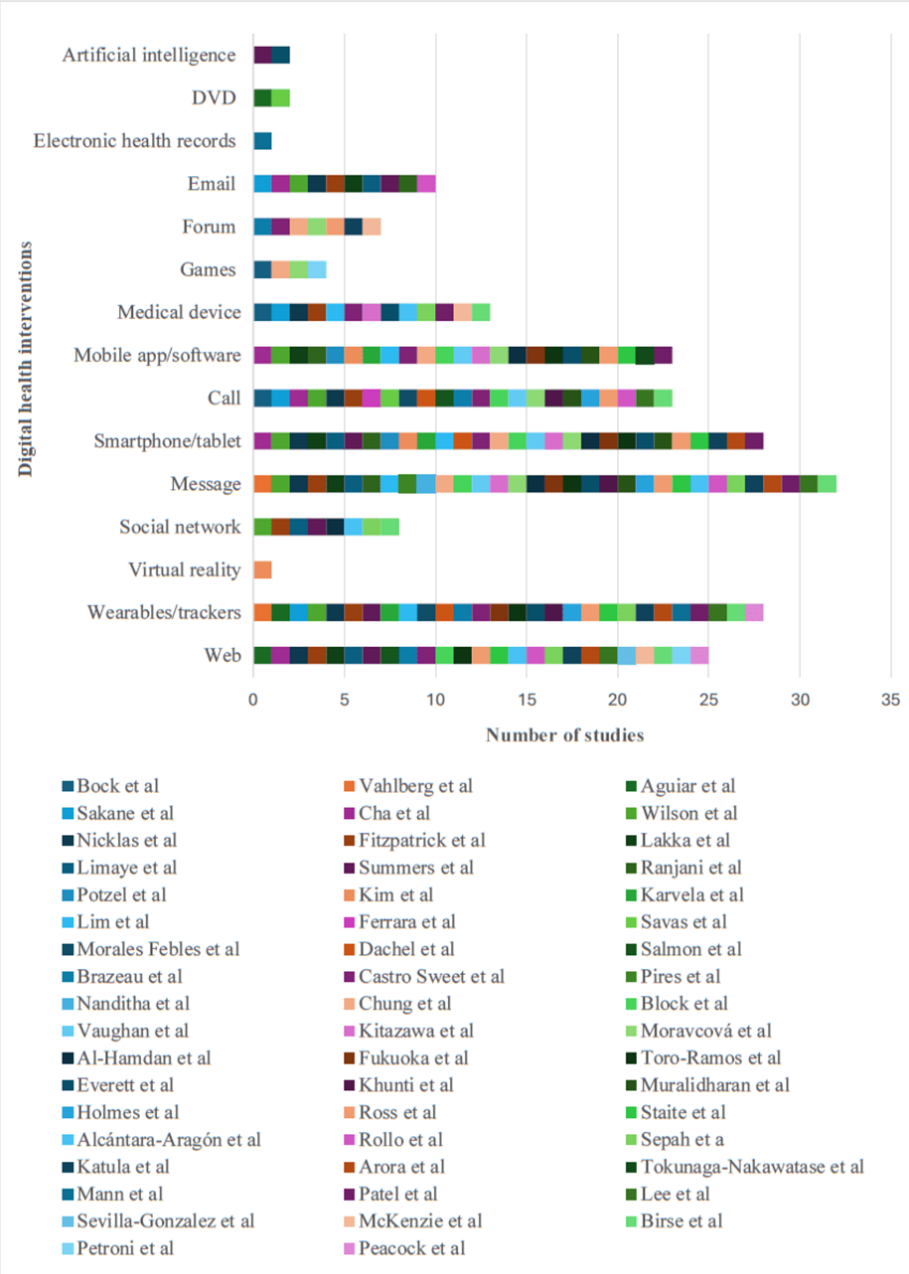


Table 2. Effects of DHIs[a] on the quadruple aims.

DHI category	Population health		Consumer experience	HCP[b] experience	Health care costs
	T2DM[c] development	Dysglycemia changes			
TCP[d]	Neutral/positive	Neutral/positive	Negative/neutral/positive	Positive	Negative/neutral
PPC[e]	Neutral	Neutral/positive	Negative/positive	N/A[f]	Negative
PHT[g]	Neutral/positive	Neutral/positive	Negative/neutral/positive	N/A	Negative
DCP[h]	Neutral	Neutral/positive	Neutral/positive	N/A	Negative
PHR[i]	N/A	Neutral	N/A	N/A	N/A
DS[j]	N/A	Neutral	N/A	N/A	N/A
TM[k]	Neutral/positive	Neutral/positive	Negative/neutral/positive	Positive	Negative/neutral

[a]DHI: digital health intervention.
[b]HCP: health care provider.
[c]T2DM: type 2 diabetes mellitus.
[d]TCP: targeted communication with persons.
[e]PPC: person-to-person communication.
[f]N/A: not applicable.
[g]PHT: personal health tracking.
[h]DCP: on-demand communication with persons.
[i]PHR: person-centered health records.
[j]DS: decision support.
[k]TM: telemedicine.

Targeted Communication With Persons

All included studies (N=53, 100%) applied TCP, including transmitting targeted health information or targeted alerts and reminders to patients. Of the 10 (18.9%) studies reviewing the effects of TCP on T2DM prevention, 9 (90%) were neutral, and 1 (10%) was positive. Of the 47 (88.7%) studies assessing dysglycemia changes, 24 (51.1%) reported neutral effects, and 23 (48.9%) posted positive effects. For example, Arora et al [34] proved after the intervention that there is a significant reduction in predicted HbA_{1c} (P<.001).

The effects of TCP on consumer experience was mixed, on HCP experience was positive, and on health care cost was neutral (n=1, 33.3%) or negative (n=2, 66.7%).

Person-to-Person Communication

Of 16 (30.2%) studies, 2 (12.5%) studies reviewing the effects of PPC on T2DM prevention were by Fitzpatrick et al [35] and McKenzie et al [36]. Results showed a neutral effect, with no significant difference in the T2DM diagnosis compared to the control group.

Of the 15 (93.8%) PPC studies assessing dysglycemia changes, 10 (66.7%) posted positive effects and 5 (33.3%) showed no discernible effect. For example, Castro Sweet et al [10] used PPC, TCP, and PHT in their DHIs; after the interventions, the change in the mean HbA_{1c} of participants reduced by 0.1% (P=.001).

A PPC study (6.3%) by Katula et al [37] reported consumer experience, with negative feedback of consumers.

A single study (6.3%), which was by Limaye et al [38], reported the effects of PPC on health care costs. The incremental cost of the DHI was GBP 35.8 (USD 47.5) per participant compared to GBP 23.3 (USD 30.9) per participant in the control group [38].

No study assessed the effect of PPC on HCP experience.

Personal Health Tracking

In 37 (69.8%) studies, PHT allowed individuals to self-monitor their health or diagnostic data (n=28, 75.7%) or actively capture/store health data to the digital platform (n=15, 40.5%).

Of the 5 (13.5%) studies on PHT reporting its effects on preventing T2DM, 1 (20%) study [39] posted a positive effect, with 4 (80%) other studies [35,36,40,41] reporting a neutral effect on T2DM development.

Of the 37 (69.8%) studies, 34 (91.9%) assessed the effectiveness of PHT in dysglycemia changes, with both positive (61.8%) and neutral (38.2%) effects. Karvela et al [42] indicated that the effect of PHT on improving HbA_{1c} was not significantly different compared to the control group (P=.31).

Of the 10 (27%) studies assessing the effects of PHT on consumer experience, the results varied; 4 (40%) studies showed a positive effect, 3 (30%) showed a negative effect, 2 (20%) were inconclusive or neutral, and 1 (10%) showed mixed effects. For example, Peacock et al [43] showed that participants using wearables/trackers feel empowered in their choice of appropriate foods (P=.04).

No studies reported HCP experience or health care costs.

On-Demand Communication With Persons

Of the 13 (24.5%) studies on DCP, 11 (84.6%) consisted of seeking supporting information and 3 (15.4%) simulated human-like conversations.

In addition, 2 (15.4%) studies [40,44] reported prevention effectiveness of DCP, and both had a neutral effect.

Of the 12 studies (92.3%) assessing the effects of dysglycemia, 9 (75%) reported positive population health outcomes, such as significant HbA_{1c} reduction compared to the control group in Kim et al [45] using virtual reality (VR) technology and Everett et al [46] using AI interventions (P<.05). Furthermore, 3 (25%) studies [40,44,47] showed the effect was neutral.

Of the 3 (23.1%) studies reporting the effectiveness of DCP on consumer experience, Cha et al [48] and Potzel et al [44] reported better experience outcomes for patients in the DHI groups, while Block et al [5] showed no effect.

Limaye et al [38] reported the effects of DCP on health care costs, with negative results. No studies reported the effects of on-demand communication on HCP experience.

Person-Centered Health Records and Health Care Provider Decision Support

One study applied PHR and HCP DS in their DHIs. Mann et al [49] reported no change in HbA_{1c} and blood glucose levels after the intervention. Effects on T2DM prevention, consumer experience, HCP experience, and health care costs were not included in the study.

Telemedicine

TM included remote consultations (n=25, 47.2%) and remote health monitoring (n=7, 13.2%).

Of the 5 (20%) studies reporting the effects of TM on T2DM development, only 1 (20%) study by Sakane et al [39] indicated that TM is effective. The other 4 (80%) studies [35,40,44,50] did not show any significant differences compared to the control group.

Of the 20 (80%) studies assessing changes in the glycemia status of participants, 11 (55%) showed that TM improves HbA_{1c} or blood glucose significantly and 9 (45%) reported neutral effects. For example, Muralidharan et al [51] and Holmes et al [52] concluded that TM, in addition to TCP, does not have a significant effect on delaying T2DM.

The effects of TM on consumer experience were varied, with 5 (71.4%) studies [39,44,48,53,54] reporting positive effects, 1 (14.2%) study [5] with no discernible effect, and 1 (14.2%) study [55] with mixed effects. For example, participants from Block et al [5] reported both positive and negative feedback.

Only 1 (14.2%) study assessed HCP experience in TM interventions, with HCP participants leaving positive feedback for TM, according to Savas et al [54].

Discussion

Principal Findings

This is the first systematic review to evaluate the effects of DHIs on the quadruple aims in T2DM prevention. Our findings enhance other recent studies, such as Nguyen et al [19], by offering a more comprehensive insight into the outcomes that are measured (and not measured), and the effects of DHIs on each outcome, in alignment with the quadruple aims of health care. This contributes to an evidence-based foundation for the future successful customization and implementation of DHIs for T2DM prevention. This is also the first systematic review of T2DM prevention using WHO's DHI classification, which significantly aids in a mutually comprehensible language for various communities involved in digital health for T2DM prevention, such as technologists, researchers, clinicians, and consumers.

Our review highlights several important findings. First, there is emerging evidence supporting the effectiveness of DHIs in preventing T2DM; however, the evidence remains limited. Although only 1 study [39] reported positive effects, 9 studies indicated neutral effects and no studies reported negative effects. This is consistent with the findings by Nguyen et al [19]. Despite this, most of these neutral studies still demonstrated clinical improvements in T2DM development, though these improvements did not reach statistical significance. The evidence is clearer on dysglycemia, where the effects were positive in nearly half of the studies and neutral in the other half. Further research will need to conclusively determine the effectiveness of DHIs in preventing T2DM.

Second, the duration of DHI may play an important role in the effects on the population health outcome. All studies successful in improving dysglycemia had a DHI duration of at least 3 months, while the study successful in T2DM prevention had a duration of 12 months [39]. Among the 10 studies with a low risk of bias in all outcomes and an intervention duration of at least 1 year, a high percentage of studies (70%) demonstrated positive effects of DHIs on dysglycemia. Comparable results about dysglycemia were reported by Van Rhoon et al [18] and Donevant et al [85]. This can be because habit formation usually takes 2-3 months [86], and significant HbA_{1c} changes require at least 3 months [87]. However, recent evidence from DPPs that have proven to be successful shows that long intervention durations are required for delaying T2DM [88], with the National Health Service recommending at least 9 months and the Centers for Disease Control and Prevention suggesting 12 months. For effective T2DM prevention, a minimum DHI duration of 9-12 months may be ideal. Future research should validate these findings.

Third, there was no evidence that DHIs are effective in preventing T2DM without HCP interaction, and most studies (69.6%) successful in improving dysglycemia involved HCP interaction (75% remote, 12.5% in person, and 12.5% both). Comparable results were reported in the review by Grock et al [89], which highlighted the importance of social interaction for successful diabetes prevention interventions. The meta-analysis by Schippers et al [90] reported that mobile apps with personal interaction tools (messages, calls, email, or in-person meetings) are more effective for weight loss than automated interaction. This underscores the critical role of HCP interaction in preventing T2DM, while also revealing the promising potential of replacing in-person HCP interactions with remote interactions for effective DHIs for T2DM prevention.

Next, all studies that reported positive population health outcomes used a minimum of 2 distinct categories of DHIs. These findings share similarities with the systematic review by Van Rhoon et al [18], which suggested that interventions with a larger number of passive and interactive digital features are more effective. In our review, TCP, which involves transmitting health information or health alerts and reminders to patients, was adopted in all included studies, demonstrating its widespread use and simplicity. TCP was used in combination with other DHI categories, such as PHT, TM, PCP, or DCP.

PHT showed evidence as a potentially useful tool for T2DM prevention and dysglycemia improvement in our review. Similarly, many studies showed that PHT successfully increases physical activity and decreases a sedentary lifestyle [91-93]. The effect of PHT on consumer experience was mixed. Automatic data capture in wearables and medical devices received more positive feedback than manual data capture, which had only neutral or negative effects. This is likely because data capture is more aligned with manual tasks, whereas wearables and medical devices are designed for automatic data collection. This result aligns with the study by Kim et al [94] on self-tracking via a web-based platform. Participants using devices with automatic data entry engaged with the platform 4 times longer than those who manually entered data [94]. This evidence strongly suggests that PHT, particularly automated tracking devices, could play a pivotal role in the prevention strategies for T2DM.

Our review suggests that TM may be effective in preventing T2DM and managing dysglycemia. This aligns with the review by Nguyen et al [19]. TM consists of remote consultations through calls and messages, and remote health monitoring. This monitoring can be achieved either automatically or manually via PHT tools, such as wearables, medical devices, or web-based apps. Consequently, there is a significant correlation between TM and PHT. Our review also shows evidence that the combination of TM, PHT, and TCP is effective in T2DM prevention. This suggests that such DHIs should not only be embraced but also be integrated with other DHIs in T2DM prevention.

Although PPC or DCP did not prove effective in preventing T2DM, they showed evidence of improving dysglycemia. PPC may be beneficial in glycemic control for diabetes management [95,96].

There is evidence that using DCP (look-up tools, human-like conversations) is helpful in diabetes prevention and management. In our review, AI used with wearables showed positive effects on glycemic status [46,56]. Similarly, evidence indicates that using AI technology in diabetes management is effective when combined with wearable technologies [97]. Advanced algorithms and data from everyday participants' activities allowed AI to provide lifestyle recommendations, which were real time, personalized, and contextual for each participant, contributing to delivering patient-centered care [98]. VR was used in 1 study, providing an immersive experience that increased participant engagement and enjoyment [99]. This highlights an advantage of VR technology. Further studies are needed to explore the potential of PPC, AI, and VR in T2DM prevention.

Health records and HCP DS were the least common in our review, with only 1 included study showing neutral effects. These DHIs target HCPs rather than consumers. Since preventing T2DM requires participants to modify lifestyles for a long period, DHIs that motivate and engage consumers may be more beneficial than DHIs targeting HCPs alone. Further studies should explore combining these DHIs with consumer-targeted interventions.

Finally, there were insufficient studies assessing HCP experience (1 study) and health care costs (3 studies). For other topics, there were several studies focusing on the effects of DHIs on HCP experience. Lampickienė et al [100] concluded that HCPs mostly report positive experiences with digital consultations, which have advantages for HCPs and patients. Studies that reported health care costs of DHIs were sparse; all 3 studies in our review indicated no positive cost outcomes in DHIs. According to a systematic review of DHIs by Gentili et al [101], there is convincing evidence of the cost-effectiveness of DHI in health care. They indicated that several types of DHIs, such as videoconferencing systems, messaging, calls, mobile apps, and web-based platforms, help reduce health care costs. Although the findings in our review were different, the small number of studies suggests that it may still be feasible to implement DHIs that are cost-effective in T2DM prevention. Further studies implementing DHIs should assess not only population health outcomes and consumer experiences but also HCP experiences and health care costs.

Limitations

There are some limitations of our review. The diagnosis criteria for T2DM varied slightly across studies. This is because of different guidelines, resources, and clinical considerations. Although our study reflected a real-world scenario, the variation in diagnosis criteria could potentially lead to data inconsistencies, because different diagnosis criteria may classify the same participant differently.

The inclusion criteria of our study permitted a wide range of variability in aspects, such as study design, study population, DHIs, and duration. DHIs are intended for real-life implementation, and the condition of RCTs is unlikely to match those routine settings, while before-and-after studies or cohort studies can provide valuable insights into special populations, such as patients with chronic liver disease [57] or renal transplant [58], groups that are often difficult to enroll in RCTs. This diversity, while inclusive, posed challenges in drawing direct comparisons and made it unfeasible to conduct a meta-analysis or certainty-of-evidence assessment.

The intervention duration fluctuated between 1 month and 48 months. Chronic diseases, such as T2DM, develop over a long period [102]. Short-term studies may not allow for the comprehensive effects of DHIs to show a clear impact on disease progression. More studies with longer durations are needed. Our study did not summarize the intensity and frequency of the DHI used in each included study. To provide a more comprehensive understanding of the effects of DHIs, further reviews and studies should examine the intensity and frequency of DHIs, rather than solely focusing on their duration.

Finally, our inclusion criteria included papers in English only. This may have potentially excluded some relevant studies.

Conclusion

The findings from this systematic review demonstrate that the effects of DHIs on the quadruple aims in T2DM prevention have proven benefits for population health, mixed results for consumer experience, and insufficient studies on HCP experience and health care costs. Further studies should prioritize improving consumer experience, while also addressing HCP experience and health care costs.

Although evidence supporting the effectiveness of DHIs in reducing the burden of T2DM remains limited, it is clear DHIs are effective in improving dysglycemia. To maximize their effectiveness in preventing T2DM and managing dysglycemia, DHIs should be strategically integrated with in-person or remote HCP interaction. The incorporation of health information transmission, alerts, and reminders for targeted individuals, along with TM and PHT strategies, is paramount. Peer group support, look-up tools, AI, and VR hold promising potential for future exploration in this field. We anticipate the advancement in these technologies will significantly influence the prevention of T2DM in the future.

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Data Availability

All data generated and analyzed during this study are included in the published paper (and its supplementary files).

Authors' Contributions

TD, LW, CS, QO, and AM designed the research; TD, LW, CS, JW, and QO extracted data; TD, LW, CS, QO, AM, and LJ analyzed the data; TD drafted the manuscript; and TD, LW, CS, QO, AM, LJ, and MV reviewed and edited the manuscript. All authors have approved the final version of the manuscript. TD is the guarantor of this work, possesses complete access to all the study data, and takes responsibility for the data's integrity and the accuracy of the data analysis. A non–peer-reviewed version of this paper was presented orally at the Australian Diabetes Congress on August 21-23, 2024.

Conflicts of Interest

None declared.

Multimedia Appendix 1

PRISMA 2020 checklist. PRISMA: Preferred Reporting Items for Systematic Reviews and Meta-Analyses.
[PDF File (Adobe PDF File), 143 KB-Multimedia Appendix 1]

Multimedia Appendix 2

Search string.
[PDF File (Adobe PDF File), 221 KB-Multimedia Appendix 2]

Multimedia Appendix 3

Data extraction form.
[PDF File (Adobe PDF File), 119 KB-Multimedia Appendix 3]

Multimedia Appendix 4

WHO's DHI classification. DHI: digital health intervention; WHO: World Health Organization.
[PDF File (Adobe PDF File), 216 KB-Multimedia Appendix 4]

Multimedia Appendix 5

Study characteristics.
[PDF File (Adobe PDF File), 491 KB-Multimedia Appendix 5]

Multimedia Appendix 6

Risk assessment.
[PDF File (Adobe PDF File), 283 KB-Multimedia Appendix 6]

Multimedia Appendix 7

Effects of DHIs on the quadruple aims. DHI: digital health intervention.
[PDF File (Adobe PDF File), 370 KB-Multimedia Appendix 7]

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Abbreviations

AI: artificial intelligence
DCP: on-demand communication with persons
DHI: Digital health intervention
DPP: diabetes prevention program
DS: decision support
HbA_{1c}: hemoglobin A_{1c}
HCP: health care provider
PHR: person-centered health records
PHT: personal health tracking
PPC: person-to-person communication
PRISMA: Preferred Reporting Items for Systematic Reviews and Meta-Analyses
RCT: randomized controlled trial
RoB 2: risk-of-bias version 2
ROBINS-I: risk of bias in nonrandomized studies of interventions
T2DM: type 2 diabetes mellitus
TCP: targeted communication with persons
TM: telemedicine
VR: virtual reality
WHO: World Health Organization

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