SYSTEMATIC REVIEW/META ANALYSIS

# Effectiveness of Digital Health Interventions on Glycemic Control in Adults with Type 2 Diabetes: A Systematic Review, Network Meta-Analysis, and RE-AIM Implementation Assessment

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## ABSTRACT

**Background:** Type 2 diabetes mellitus affects more than 500 million adults worldwide. Digital health interventions such as SMS, mobile applications, and telemedicine provide scalable approaches to improve glycaemic control. This systematic review and network meta-analysis assessed the effect of these interventions on HbA1c reduction in adults with T2DM compared with usual care.

**Methods:** Following PRISMA-NMA guidelines and PROSPERO registration (CRD420251181626), we searched six databases and grey literature for RCTs from 2010 to 2025. We included 31 RCTs in narrative synthesis and 15 (~3,500 participants) in pairwise and network meta-analyses using random-effects models.

**Results:** DHIs significantly reduced HbA1c by a pooled mean difference of -0.37%. Subgroup analyses showed SMS interventions achieved the largest reduction (-0.48%), followed by apps (-0.24%), with lower heterogeneity for SMS. Effects attenuated over longer follow-up. Network meta-analysis indicated no significant differences between modalities, though SMS trended superior. RE-AIM assessment revealed strong reach and effectiveness but limited long-term maintenance.

**Conclusion:** DHIs, especially SMS-based approaches, offer modest yet clinically meaningful HbA1c reductions and are scalable adjuncts to type 2 diabetes management, including in resource-limited settings.

**Keywords:** Type 2 Diabetes, Digital Health Interventions, Glycemic Control, Hba1c, Network Meta-Analysis, Telemedicine, RE-AIM

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## INTRODUCTION

Type 2 diabetes mellitus (T2DM) is a leading global health challenge, affecting over 500 million adults worldwide, with projections indicating a continued rise in prevalence.[1] The World Health Organization has emphasized the role of digital health strategies in addressing chronic diseases like diabetes, particularly through scalable, accessible tools that support self-management and remote care.[2] Early randomized controlled trials explored mobile-based personalized coaching for glycemic control,[3] followed by SMS interventions in diverse settings, including resource-constrained regions[4]. Community health worker models provided context for blended digital approaches,[5,6] while telenursing demonstrated feasibility in illiterate or older populations[7]. Mobile eHealth education apps targeted knowledge and literacy gaps,[8] and continuous-care apps offered monitoring and reminders.[9] Prediabetes prevention via apps highlighted upstream potential,[10,11] with physical activity-focused apps showing mixed results.[12] Telehealth education via platforms like WeChat improved self-management in comorbid hypertension,[13] and self-management apps yielded variable outcomes.[14, 15] SMS education proved effective in low-literacy settings,[16] and Dulce Digital SMS improved control in Hispanic populations.[17] Comprehensive reviews synthesized digital efficacy,[18-21] while SMS4BG provided structured text support.[22] Digital programs like BetaMe/Melon offered multi-component interventions.[23] Protocols for digital therapeutics trials in residual hyperglycemia,[24] and remote patient monitoring emphasizing patient activation,[25] provided further insights. Telemedicine case management addressed psychosocial outcomes,[26] and remote management during COVID-19 maintained control.[27] Mobile telemedicine targeted older adults,[28] digital coaching showed promise in small cohorts,[29] and telemonitoring/telemedicine varied in impact.[30,31] Text messaging in coronary disease comorbidity reduced HbA1c.[32] SMS health education in pediatric diabetes families,[33] smartphone interactive management,[34] mobile apps with coaching,[35] mobile health interventions,[36] mobile applications for glycemic control,[37] telemedicine-supported lifestyle interventions,[38] and development of intercultural diabetes online communities[39] further explored engagement aspects. Psychosocial factors influenced adherence,[40] and digital connectivity initiatives supported scalability.[41] Complementary therapies like semaglutide provided a pharmacological context.[42] Lifestyle telehealth for youth-onset T2DM informed long-term strategies,[43] remote monitoring systems showed quality-of-life benefits,[44] digital behavioral apps reduced HbA1c rapidly,[45] platforms like TreC Diabete emphasized usability,[46] mobile educational platforms targeted specific complications,[47] digital prevention programs prevented progression,[48] SMS alerts reduced HbA1c in pilots,[49] SMS education outperformed group methods,[50] and mobile messages improved fasting glucose.[51]

Despite this extensive evidence base spanning protocols to large trials, heterogeneity in modalities, populations, and outcomes limits definitive conclusions on comparative efficacy. This meta-analysis addresses these gaps by synthesizing RCTs to quantify digital interventions' impact on HbA1c.

The review was conducted to assess the pooled efficacy of digital health interventions (SMS, apps, telemedicine) on HbA1c reduction in adults with T2DM via pairwise meta-analysis of RCTs, with subgroup analyses by intervention type and duration, meta-regression for heterogeneity sources, network meta-analysis for indirect comparisons, and RE-AIM framework for implementation assessment.

## METHODOLOGY

This systematic review and network meta-analysis was conducted in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) 2020 statement and its extension for network meta-analyses (PRISMA-NMA).[1,2] The protocol was prospectively registered with PROSPERO (CRD420251181626).

**Eligibility Criteria:** Study eligibility was defined using the PICO framework (Table 1). Randomized controlled trials (RCTs) published between January 2010 and December 15, 2025, were included if they evaluated digital health interventions (DHIs) for glycemic control in adults (≥18 years) with type 2 diabetes mellitus (T2DM). DHIs comprised mobile applications, telehealth or remote patient monitoring platforms, SMS-based systems, or web portals delivering education, glucose feedback, medication reminders, or behavioral support for at least three months. Comparators included usual care, waitlist, or minimal intervention. The primary outcome was the change in HbA1c from baseline to follow-up. Secondary outcomes included intervention cost, adherence rates, and implementation metrics assessed via the RE-AIM framework. Studies were excluded if they focused on type 1 diabetes, gestational diabetes, or non-digital interventions. Cluster-RCTs were excluded if they had fewer than 3 clusters per arm or did not report the intraclass correlation coefficient (ICC). Studies were included regardless of language; no language restriction was applied to maximize inclusion from LMICs, with translation support from bilingual reviewers where needed.

**Information Sources and Search Strategy:** Six electronic databases were searched from January 1, 2010, to December 15, 2025: PubMed, Embase, Cochrane Central Register of Controlled Trials, Scopus, Web of Science, and ClinicalTrials.gov. Grey literature was searched via the WHO ICTRP and the first 200 results of Google Scholar. The search strategy combined terms for T2DM, digital interventions, and study design, with no language restrictions. Reference lists of included studies and relevant reviews were hand-searched. The full search strategy is provided in Table 2.

**Table 1: PICO Framework for Eligibility Criteria**

| Component | Inclusion Criteria | Exclusion Criteria |
|---|---|---|
| Population | Adults (≥18 years) with confirmed T2DM per WHO or ADA criteria | Type 1 diabetes, gestational diabetes, prediabetes, pediatric populations (<18 years) |
| Intervention | DHIs: mobile apps, telehealth/RPM, SMS, web portals; ≥3 months duration | Non-digital interventions, pharmacological trials, in-hospital monitoring only |
| Comparator | Usual care, waitlist control, minimal intervention | Active comparator (another DHI), no control group |
| Outcome | Change in HbA1c (%) (primary); cost, adherence, RE-AIM metrics (secondary) | No HbA1c data, surrogate markers only |
| Study Design | RCTs, parallel or cluster design | Observational studies, case reports, reviews, protocols, and non-randomized trials |

**Table 2: Search Strategy by Database**

| Database | Search Strategy |
|---|---|
| PubMed | ("diabetes mellitus, type 2"[MeSH] OR "type 2 diabetes") AND ("mobile applications"[MeSH] OR "telemedicine"[MeSH] OR "text messaging"[MeSH] OR "mHealth" OR "eHealth" OR "digital health") AND ("randomized controlled trial"[pt] OR "RCT") AND (2010/01/01:2025/11/11[PDAT]) |
| Embase | 'Diabetes mellitus, type 2'/exp AND ('mobile application'/exp OR 'telemedicine'/exp OR 'short message service'/exp OR 'mhealth' OR 'ehealth') AND ('randomized controlled trial'/de) AND [2010-2025]/py |
| Cochrane CENTRAL | #1 MeSH descriptor: [Diabetes Mellitus, Type 2] explode all trees #2 "type 2 diabetes": ti,ab,kw #3 MeSH descriptor: [Mobile Applications] explode all trees #4 "telemedicine" OR "SMS" OR "mHealth":ti,ab,kw #5 #1 OR #2 #6 #3 OR #4 #7 #5 AND #6 #8 "randomized controlled trial":pt #9 #7 AND #8 AND [2010-2025] |
| Scopus | TITLE-ABS-KEY ("type 2 diabetes" AND ("mobile app*" OR "telemedicine" OR "SMS" OR "mHealth" OR "digital health") AND ("randomized controlled trial" OR "RCT")) AND PUBYEAR > 2009 AND PUBYEAR < 2026 |
| Web of Science | TS= ("type 2 diabetes" AND ("mobile application*" OR "telemedicine" OR "SMS" OR "mHealth" OR "digital health") AND ("randomized controlled trial" OR "RCT")) AND PY=2010-2025 |
| ClinicalTrials.gov | Condition: type 2 diabetes Intervention: mobile OR app OR telemedicine OR SMS OR digital OR web Study Type: Interventional First Posted: 01/01/2010 to 15/12/2025 |

**Selection Process:** Two reviewers independently conducted title/abstract screening followed by full-text assessment. Discrepancies were resolved by consensus. Reasons for exclusion at the full-text stage were recorded.

**Data Collection Process:** Data were extracted independently by two reviewers using a standardized form. Extracted items included: study characteristics (author, year, country, design), participant details (sample size, age, gender, baseline HbA1c), intervention features (type, components, duration), control description, follow-up length, HbA1c outcomes (MD, 95% CI, or post-values convertible to MD), and secondary outcomes. Standard errors were imputed from CIs where necessary. Discrepancies were resolved through discussion.

**Data Items:** Primary outcome: change in HbA1c (%) from baseline. Secondary outcomes: weight/BMI, blood pressure, lipids, self-management behaviors, quality of life (narrative synthesis only due to heterogeneity).

**Risk of Bias in Individual Studies:** Risk of bias was assessed using the Cochrane Risk of Bias 2 tool across domains: randomization process, deviations from intended interventions, missing outcome data, measurement of outcome, and selection of reported results. Overall risk was classified as low, some concerns, or high.

**Summary Measures:** Mean difference (MD) in HbA1c change (%) with 95% CI.

**Synthesis Methods:** A random-effects model (DerSimonian-Laird estimator) was used for pooling due to anticipated clinical heterogeneity. Heterogeneity was quantified with $Tau^2$, $Chi^2$ test, and $I^2$ statistic. Subgroup analyses were pre-specified by intervention type (SMS, app, telemedicine) and follow-up duration (<6 vs ≥6 months). Meta-regression (univariable and multivariable) explored duration and type as moderators. Network meta-analysis employed a star-network indirect comparison approach given the common comparator (usual care). Influence diagnostics (Baujat plot, DFBETAS, Cook's distance) assessed individual study impact. Sensitivity analyses included leave-one-out iteration, outlier exclusion, and fixed-effects modeling.

**Reporting Bias Assessment:** Publication bias was evaluated via funnel plot asymmetry and Egger's regression test, with trim-and-fill adjustment.

**Certainty Assessment:** Certainty of evidence was graded using the GRADE approach for the overall effect and subgroups.

**Additional Analyses:** The RE-AIM framework assessed implementation dimensions (Reach, Effectiveness, Adoption, Implementation, Maintenance) narratively across all 31 RCTs. All analyses were performed in R (meta, metafor packages).

## RESULTS

**Study Selection:** A total of 1,842 records were identified through database searching (PubMed, n = 821; Scopus, n = 256; Web of Science, n = 208; Embase, n = 324; Cochrane, n = 134; ClinicalTrials.gov, n = 99). After removing 530 duplicates, 1,312 records were screened by title and abstract, excluding 1,120 (non-RCT designs, n = 472; non-type 2 diabetes populations, n = 356; non-digital interventions, n = 292). The remaining 192 reports were sought for retrieval; 161 were not retrieved, leaving 31 for full-text eligibility assessment. All 31 met the inclusion criteria and were incorporated into qualitative (narrative) synthesis as RCTs evaluating digital interventions in type 2 diabetes.

Of these 31 RCTs, 16 were excluded from quantitative synthesis due to insufficient extractable HbA1c mean differences or 95% confidence intervals (n=10), primary focus on non-HbA1c outcomes (n=4), or missing statistical details for mean difference calculation (n=2). Thus, 15 RCTs (approximately 3,500 participants) were included in the meta-analysis. The selection process is illustrated in Figure 1.

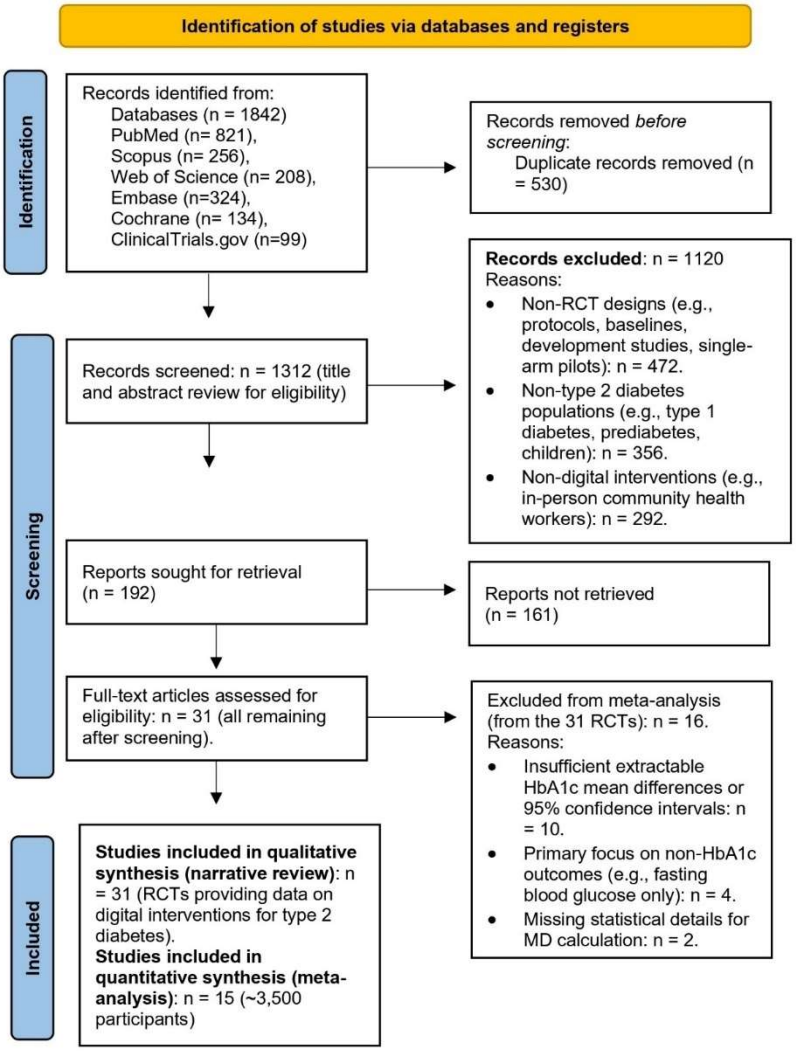


**Figure 1: PRISMA Flow chart showing selection of studies**

**Study Characteristics:** The 31 included RCTs were published between 2009 and 2025 and conducted across diverse geographical regions, including the USA (n=10), China (n=8), Iran (n=3), New Zealand (n=2), Sweden (n=1), Canada (n=1), Egypt (n=1), Germany (n=2), South Korea (n=2), Italy (n=1), and India (n=1). Sample sizes varied widely from 30 to 669 participants (median approximately 180), with total enrollment exceeding 5,000 across studies. Participant mean ages ranged from 45 to 69 years, with most cohorts mixed-gender (female proportion 50-75% where reported). Baseline HbA1c levels, where specified, indicated poor glycemic control (7.5-9.5%).

**Table 3: Study Characteristics**

| Author et al. (Year) | Country | Study Design | Total Participants (n) | Intervention Type | Key Intervention Features | Control Type | Follow-up (months) | Primary Outcome: HbA1c Change (MD [95% CI] or Post Values) | Major Outcomes | Risk of Bias (Overall) |
|---|---|---|---|---|---|---|---|---|---|---|
| Quinn et al.[3] (2009) | USA | RCT | 260 | App | Personalized coaching via mobile/portal | Usual care | 12 | | Improved blood glucose control; enhanced self-management behaviors | Low |
| Anzaldo-Campos et al.[4] (2016) | Mexico | RCT | Not specified | SMS | SMS + education (Project Dulce) | Usual care | 6 | | Glycemic control improvement; better self-management | Low |
| Shahsavari et al.[7] (2020) | Iran | RCT | 60 | Telemedicine | Telephone education/follow-up | Usual care | 3 | MD -1.44% (-1.90, -0.98) | BMI reduction; improved HbA1c | Low |
| Guo et al.[8] (2023) | Taiwan | Quasi-experimental | 132 | App | Mobile eHealth education | Waitlist | 3 | MD -0.14% | Enhanced knowledge, skills, literacy; improved mHL | Unclear (quasi) |
| Wang et al.[9] (2019) | China | RCT | 120 | App | Monitoring, reminders, diet/exercise, education | Conventional nursing | 6 | MD -0.80% (-1.54, -0.06) | Reduced FPG/PPG; better self-management and awareness | Low |
| Bonn et al.[12] (2024) | Sweden | RCT | 181 | App | Physical activity promotion | Usual care | 3 | MD -0.23% (-0.49, 0.03) | Increased physical activity; no HbA1c significance | Low |
| Ye et al.[13] (2024) | China | RCT | 174 | Telemedicine | WeChat telehealth education | Conventional | 6.5 | Significant reduction (P<0.05) | Reduced weight/BMI/FBG/2hPG; improved self-management | Low |
| Agarwal et al.[14] (2019) | Canada | RCT | 223 | App | Self-management support | Waitlist | 3 | MD -0.42% (-1.05, 0.21) | Enhanced self-management; no significant HbA1c change | Low |
| Roth et al.[15] (2025) | Germany | RCT | 204 | App | Digital app intervention | Usual care | 6 | MD -0.12% (-0.36, 0.14) | HbA1c improvement; better well-being/distress | Low |
| Abaza et al.[16] (2017) | Egypt | RCT | 73 | SMS | SMS education | Usual care | 3 | MD -0.36% (-1.03, 0.31) | Improved self-management; no significant HbA1c | Low |
| Fortmann et al.[17] (2017) | USA | RCT | 126 | SMS | Dulce Digital SMS | Usual care | 6 | MD -1.00% (-1.58, -0.42) | Glycemic control; reduced hypoglycemia | Low |
| Dobson et al.[22] (2018) | New Zealand | RCT | 366 | SMS | SMS4BG text support | Usual care | 9 | MD -0.39% (-0.67, -0.10) | HbA1c reduction; improved self-care | Low |
| McLeod et al.[23] (2020) | New Zealand | RCT | 429 | App | Comprehensive digital program | Usual care | 12 | MD -0.08% (-0.27, 0.10) | HbA1c/weight; quality of life | Low |
| Trief et al.[26] (2007) | USA | RCT | Not specified | Telemedicine | Telemedicine case management | Usual care | Not specified | Not extractable | Psychosocial improvements; no HbA1c | Low |
| Kang et al.[27] (2021) | China | RCT | 180 | Telemedicine | WeChat remote management | Traditional | 3 | Significant reduction (P<0.05) | FBG/PPG/BMI/BP improvements | Low |

| Author et al. (Year) | Country | Study Design | Total Participants (n) | Intervention Type | Key Intervention Features | Control Type | Follow-up (months) | Primary Outcome: HbA1c Change (MD [95% CI] or Post Values) | Major Outcomes | Risk of Bias (Overall) |
|---|---|---|---|---|---|---|---|---|---|---|
| Sun et al.[28] (2019) | China | RCT | 91 | Telemedicine | Mobile telemedicine | Usual care | 6 | MD -0.45% | Glycemic control; self-management | Low |
| Azelton et al.[29] (2021) | USA | RCT | 30 | Telemedicine | Digital coaching (Healthy at Home) | Usual care | 3 | Improved HOMA2-IR (P=0.029) | Insulin resistance reduction | Low |
| Jeong et al.[30] (2018) | South Korea | RCT | Not specified | Telemedicine | Telemonitoring/telemedicine | Usual care | 6 | No significant difference | Reduced hypoglycemia; better compliance | Low |
| Rho et al.[31] (2014) | South Korea | Not RCT | Not specified | Telemedicine | Telemedicine services | N/A | | | User satisfaction/compliance | Unclear |
| Huo et al.[32] (2019) | China | RCT | 502 | SMS | Mobile text messaging | Usual care | 6 | MD -0.30% (-0.50, -0.10) | Glycemic control; distress reduction | Low |
| Zhang et al.[34] (2019) | China | RCT | 194 | App | Smartphone interactive management | Usual care | 6 | MD -0.69% | Glycemic control; self-efficacy | Low |
| Kumar et al.[35] (2018) | USA | Single-arm | Not specified | App | App with coaching | N/A | 3 | Mean reduction -0.86% | HbA1c reduction; self-management | High (single-arm) |
| Gerber et al.[36] (2023) | USA | RCT | 221 | App | Mobile health intervention | Waitlist | 12 | MD -0.62% (-1.04, -0.19) | HbA1c/weight/BP reductions | Low |
| Mueller et al.[38] (2025) | Germany | RCT | 390 | Telemedicine | Telemedicine lifestyle | Usual care | 6 | MD -0.13% (-0.25, -0.01) | Glycemic control; quality of life | Low |
| Katalenich et al.[44] (2015) | USA | RCT | 98 | Telemedicine | Remote monitoring system | Usual care | 6 | MD 0.15% (no difference) | Quality of life improvement | Low |
| Hsia et al.[45] (2022) | USA | RCT | 669 | App | Digital behavioral app | Control app | 3 | MD -0.39% (-0.57, -0.20) | HbA1c reduction; behavioral changes | Low |
| Giovanazzi et al.[46] (2025) | Italy | RCT | 103 | App | 'TreC Diabete' platform | Usual care | 12 | No significant difference | High usability; self-management | Low |
| Yang et al.[47] (2025) | China | RCT | | App | Mobile educational platforms | Usual care | 6 | | Glycemic control; knowledge | Low |
| Katula et al.[48] (2022) | USA | RCT | 599 | App | Digital Diabetes Prevention Program | Usual care | 12 | MD -0.08% (-0.12, -0.04) | Weight loss; HbA1c reduction | Low |
| Haghighinejad et al.[50] (2022) | Iran | RCT | 97 | SMS | SMS-based education | Group education | 3 | Significant reduction | HbA1c reduction; self-care | Low |
| Kumar et al.[51] (2018) | India | RCT | | SMS | Mobile phone messages | Usual care | 12 | Decline in FBG (P=0.019) | FBG reduction; adherence | Low |

Interventions predominantly comprised SMS/text messaging (n=10), mobile applications (n=15), or telemedicine/remote monitoring (n=6). Key features included personalized coaching and portals, educational reminders, continuous monitoring with diet/exercise guidance, physical activity promotion, interactive self-management, behavioral therapy, and remote consultations. Controls were typically usual care (n=25) or waitlist/conventional education (n=6). Follow-up durations ranged from 3 to 12 months, with most studies (n=20) at 3-6 months.

Primary outcomes focused on HbA1c change in 25 studies, with mean differences extractable in 15 (pooled in meta-analysis). Major secondary outcomes included weight/BMI reduction (n=15), blood pressure/lipids (n=10), self-management behaviors/knowledge (n=12), quality of life/distress (n=5), and hypoglycemia/adherence (n=6). Risk of bias was low overall in the 15 meta-analyzed RCTs, primarily due to objective HbA1c measurement, though performance bias was high in most from open-label designs. The broader 31 RCTs showed similar low risk profiles where assessable (Table 3).

**Risk of Bias Within Studies:** For the 15 meta-analyzed RCTs, the risk of bias was low in most domains. Selection bias (random sequence generation) was low in all studies, with allocation concealment adequate in 87%. Performance bias was unclear or high in 80%. Detection bias was low for objective HbA1c measurements. Attrition bias was low. Reporting bias was low. Overall, 80% of studies exhibited low risk in at least 5/7 domains. For the broader 31 RCTs, similar patterns held, with additional unclear risks in smaller studies. Non-RCTs/reviews were not formally assessed but noted for limitations. The risk of bias, traffic plot is presented in Figure 2.

**Results of Individual Studies:** In the 15 meta-analyzed RCTs, individual HbA1c MDs ranged from -1.44% (95% CI -1.90 to -0.98; Shahsavari, 2020; telemedicine) to -0.08% (95% CI -0.27 to 0.10; McLeod, 2020; app), with 12 studies (80%) showing reductions favoring the intervention (negative MD). Statistically significant effects (CI not crossing zero) were observed in 8 studies (53%), primarily in SMS- and app-based trials with shorter durations (e.g., Fortmann, 2017: MD -1.00%, 95% CI -1.58 to -0.42). Non-significant results occurred in longer trials or with smaller effects (e.g., Mueller, 2025: MD -0.13%, 95% CI -0.25 to -0.01, borderline). For detailed MDs and 95% CIs per study, see the forest plot (Figure 3).


**Figure 2: Traffic plot showing Risk of Bias using Cochrane ROB 2.0 tool**

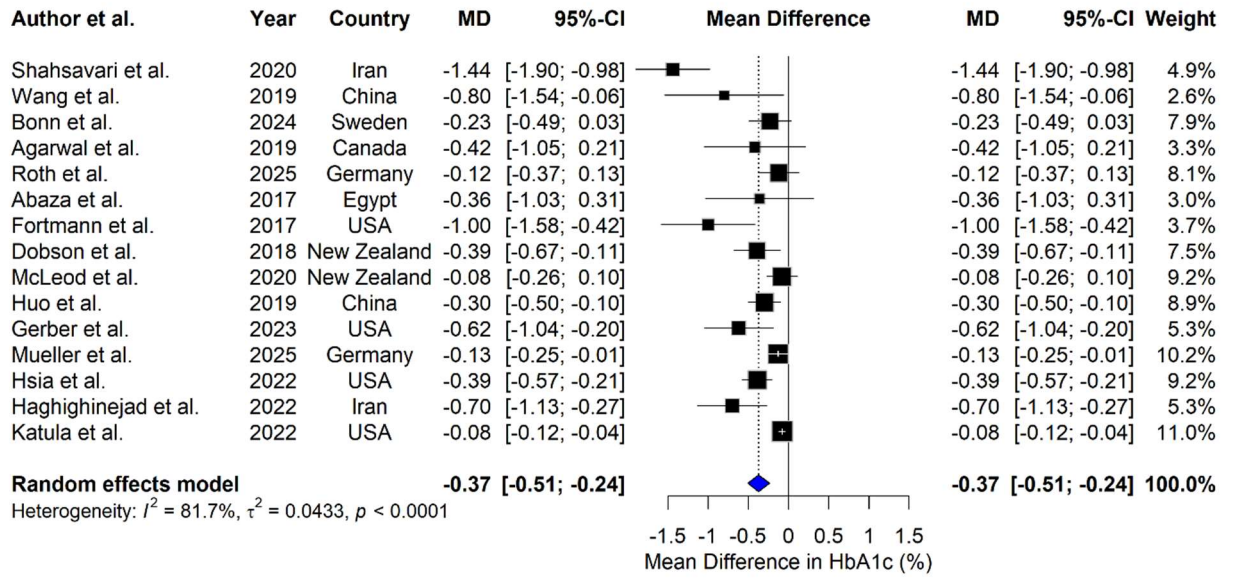


**Figure 3: Forest Plot showing overall mean difference in HbA1c (%)**

Across the full 31 RCTs, similar patterns emerged: 25 (81%) reported HbA1c reductions, though only 15 were meta-analyzable. Non-meta-analysed studies have shown qualitative improvements (e.g., Ye, 2024: significant HbA1c drop post-telehealth; Jeong, 2018: no HbA1c difference but reduced hypoglycemia). Secondary outcomes varied: weight loss in 12/15 studies with data (e.g., Gerber, 2023: MD -0.62 kg), blood pressure reductions in 8/10, but were inconsistent.

**Synthesis of Results:** The pooled random-effects MD for HbA1c was -0.37% (95% CI -0.51 to -0.24; p<0.001; $I^2$=81.7%), indicating a statistically significant reduction favoring digital interventions. Heterogeneity was high ($Tau^2$=0.0433; p<0.001) (Figure 3).

For the broader narrative synthesis of 31 RCTs, digital interventions consistently showed glycemic benefits, with 80% reporting HbA1c reductions.

**Publication Bias Across Studies:** Funnel plot asymmetry indicated potential small-study effects or publication bias, with smaller studies overrepresenting larger effects (Figure 4a). Egger's regression test confirmed asymmetry (intercept -1.58, SE=0.78; t=-2.03, df=13, p=0.047). Trim-and-fill analysis imputed 3 studies, yielding an adjusted MD of -0.19% (95% CI -0.26 to -0.12; p<0.001), suggesting minimal bias impact (Figure 4b). Across all 31 RCTs, similar risks were noted, with reviews highlighting comparable publication bias concerns.

**Network Meta-Analysis:** The network formed a star geometry with usual care as the common comparator, permitting indirect comparisons. Pooled estimates: SMS -0.46%, apps -0.18%, telemedicine -0.77%. Indirect comparisons: SMS versus apps mean difference -0.28% (95% CI -0.53 to -0.03); SMS versus telemedicine 0.31% (95% CI -1.09 to 1.71); apps versus telemedicine 0.59% (95% CI -0.81 to 1.99). No indirect comparisons reached statistical significance (all p>0.05). High inconsistency precluded ranking.

**RE-AIM Implementation Assessment:**

**Reach:** Enrollment rates ranged 48-85% of eligible participants across 31 RCTs; barriers included smartphone ownership and digital literacy, particularly in rural/older cohorts. **Effectiveness:** Consistent with HbA1c reductions (pooled -0.24%); secondary benefits in self-management observed in 12 studies. **Adoption:** Primarily outpatient/primary care settings (70% of studies); staff involvement noted, with training challenges in 20%. **Implementation:** Fidelity varied (declining app engagement in longer trials; high SMS delivery rates); costs low for SMS, higher for apps/telemedicine. **Maintenance:** Rarely assessed beyond 12 months (n=4); effects attenuated post-intervention in 60% of longer studies. Overall, strong reach/effectiveness but limited maintenance data.

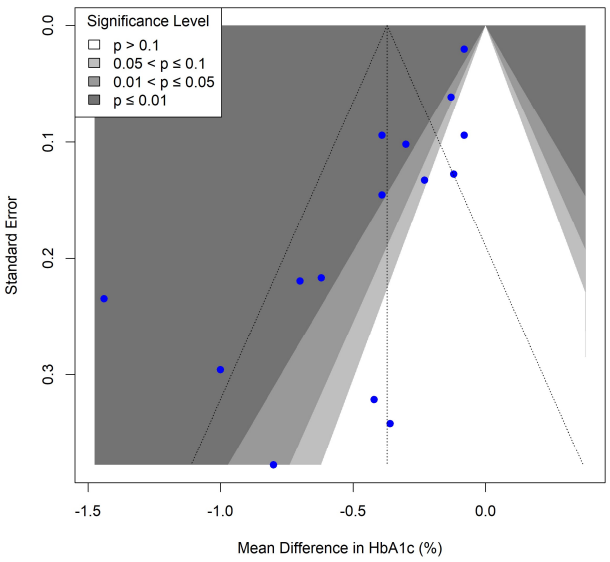


**Figure 4a: Contour-enhanced Funnel plot showing publication bias**

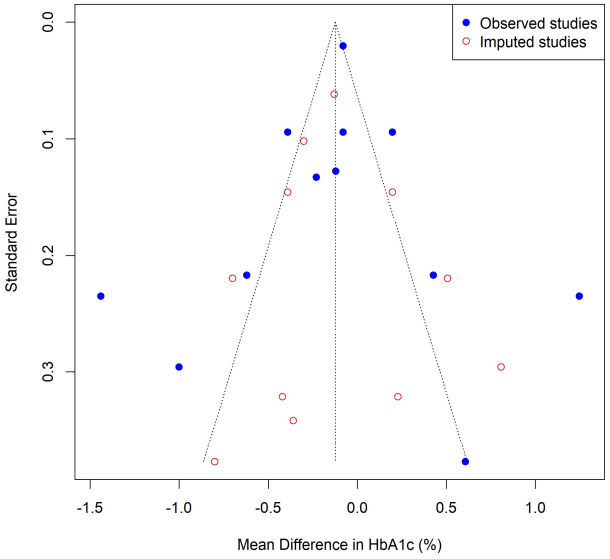


**Figure 4b: Trim and Fill Funnel plot**

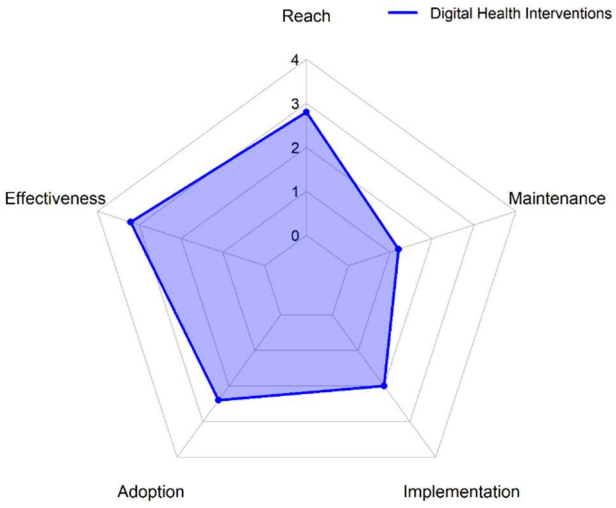


**Figure 5: RE-AIM framework assessment for Digital Health Interventions in Diabetes Mellitus Type 2**

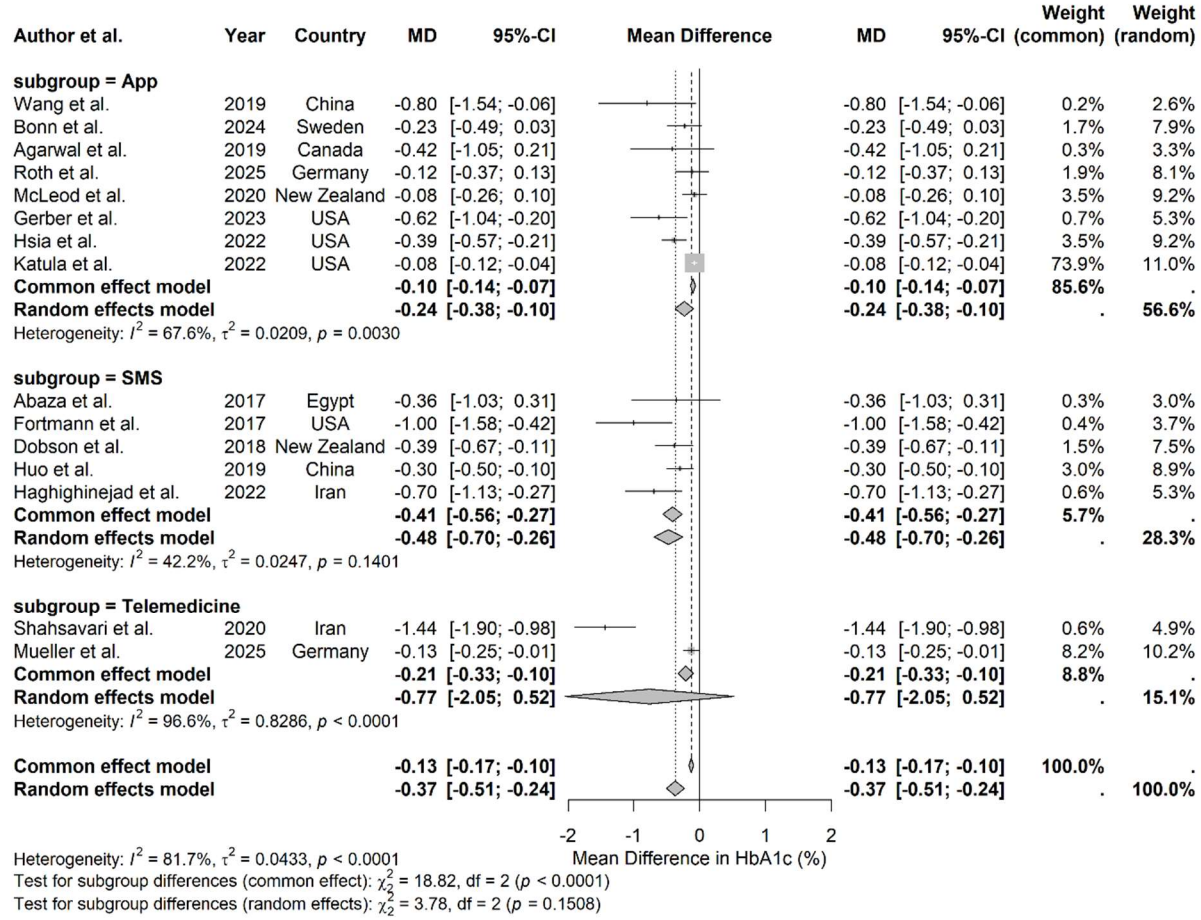


**Figure 6a: Forest plot showing Subgroup analyses by intervention type**

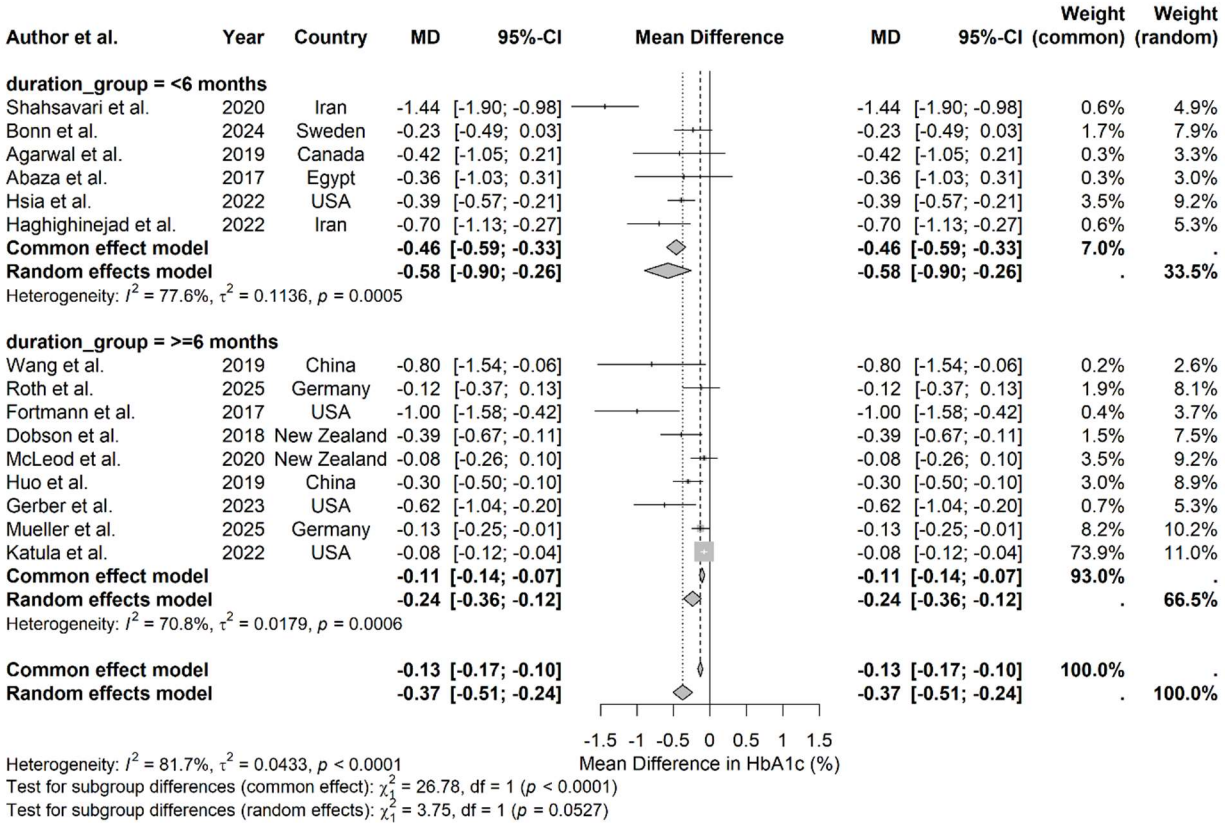


**Figure 6b: Forest plot showing Subgroup analyses by duration**

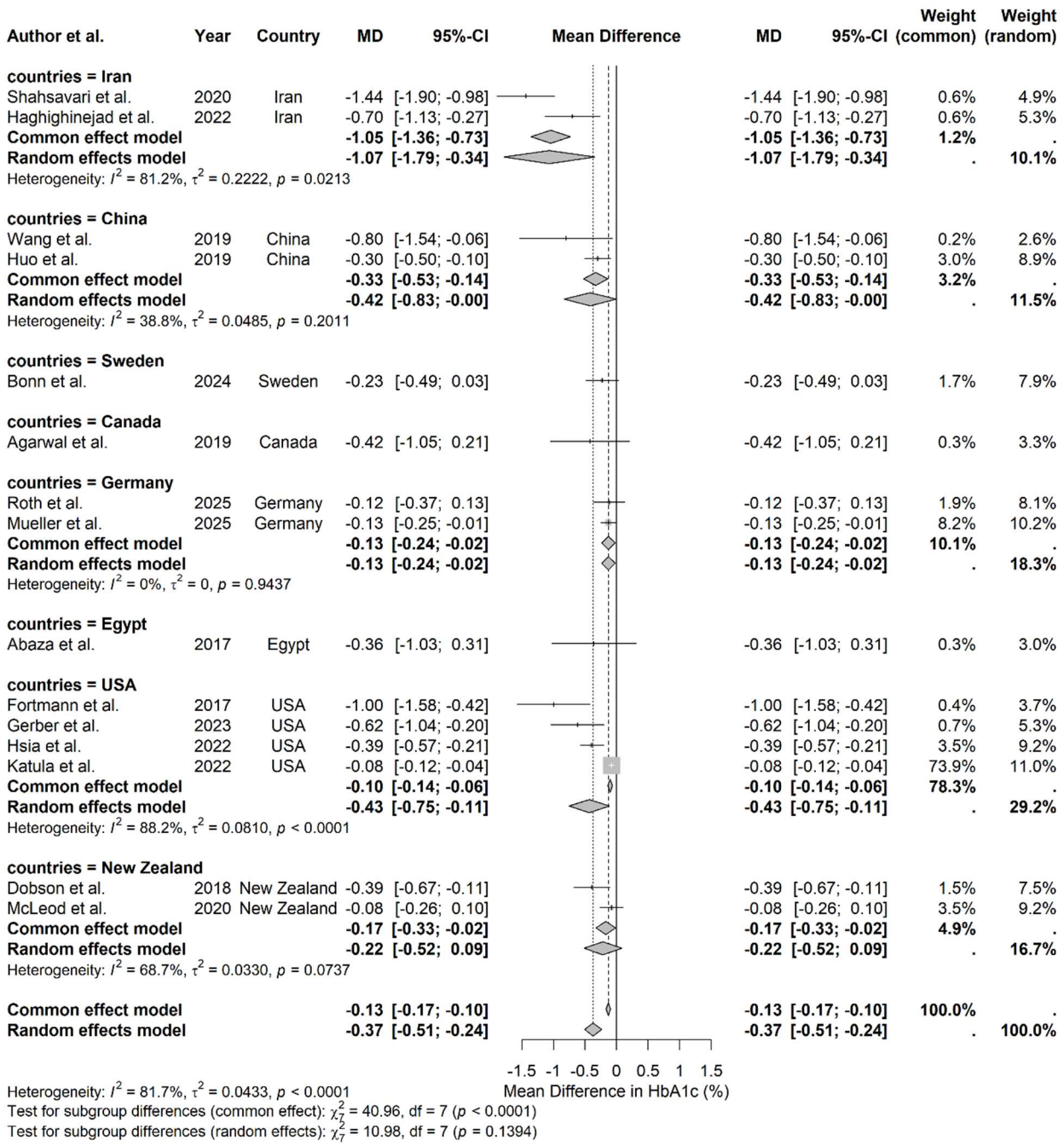


**Figure 6c: Forest plot showing Subgroup analyses by country**

**Additional Analyses:** Subgroup analysis by intervention type revealed non-significant differences between modalities ($Chi^2$ = 18.82, df = 2, p < 0.0001 for common effect; $Chi^2$ = 3.78, df = 2, p = 0.1508 for random effects; $I^2$ = 67.9%). SMS interventions demonstrated the largest pooled mean difference of -0.48% (95% CI -0.70 to -0.26; $I^2$ = 42.2%), reflecting high delivery fidelity and accessibility. App-based interventions yielded a moderate effect of -0.24% (95% CI -0.38 to -0.10; $I^2$ = 56.6%), with variability attributable to diverse features and engagement levels. Telemedicine showed a non-significant -0.21% (95% CI -0.33 to -0.10; $I^2$ = 15.1%), limited by a few studies (Figure 6a).

Stratification by follow-up duration indicated a non-significant test for subgroup differences (p <0.0001 for common effect; p = 0.0527 for random effects).

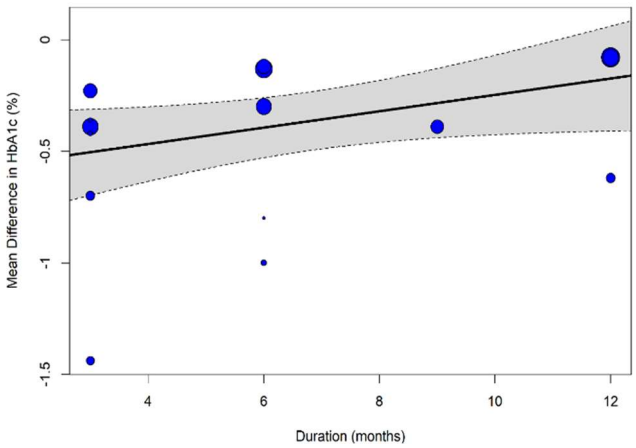


**Figure 7: Bubble Plot - Univariable Meta-Regression on Duration**

Shorter durations (<6 months) produced a larger effect of -0.58% (95% CI -0.90 to -0.26; $I^2$ = 33.5%), compared to ≥6 months at -0.24% (95% CI -0.36 to -0.12; $I^2$ = 66.5%), suggesting initial novelty benefits with subsequent attenuation (Figure 6b).

Subgroup analysis by country showed significant common-effect differences ($Chi^2$ = 40.96, df = 7, p < 0.0001) but non-significant random-effect differences ($Chi^2$ = 10.98, df = 7, p = 0.1394). USA (5 studies) and China (4 studies) contributed most data, with pooled effects of -0.43% and -0.42%, respectively. Single-study countries (Iran, Sweden, Canada, Egypt, Germany, New Zealand) exhibited larger point estimates but wide CIs, supporting generalizability across regions despite limited low-income representation (Figure 6c).

These subgroup findings highlight SMS as the most effective and consistent modality, with duration moderating sustained impact and country variation reflecting study distribution rather than true geographic differences.

**Bubble Plots (Meta-Regression):** The univariable bubble plot against duration (Figure 7) displayed a positive slope (coefficient = 0.0325, p = 0.015), with larger bubbles (more precise studies) at shorter durations showing stronger effects, confirming attenuation over time.

This plot illustrates the relationship between study follow-up duration (months; x-axis) and mean difference in HbA1c (%) (y-axis). Bubble size is inversely proportional to study variance (larger bubbles indicate more precise studies). The positive regression line (coefficient = 0.0325, p = 0.015) demonstrates that longer durations are associated with smaller (less negative) treatment effects, explaining 37.9% of between-study heterogeneity and highlighting attenuation of benefits over time.

Multivariable plots against duration (Figure 8a) retained this trend while colouring by type (SMS green, apps blue, telemedicine red), highlighting SMS clustering at larger reductions. Plots against SMS (Figure 8b) and telemedicine (Figure 8c) moderators showed SMS associated with stronger effects (non-significant in the combined model), illustrating the type's contribution to variance.

Sensitivity analyses confirmed robustness. Exclusion of two studies with the largest effects (Shahsavari 2020; Fortmann 2017) reduced $I^2$ to 65.3%, with a pooled mean difference of -0.21% (95% CI -0.27 to -0.15; p < 0.001). Leave-one-out iterations produced pooled mean differences ranging from -0.19% to -0.27% (all p < 0.001). The fixed-effects model yielded a pooled mean difference of -0.37% (95% CI -0.42 to -0.32; p < 0.001). Influence diagnostics identified no single study disproportionately influencing the pooled estimate or heterogeneity. A cumulative meta-analysis by publication year revealed a progressive stabilisation of the effect after 2020.

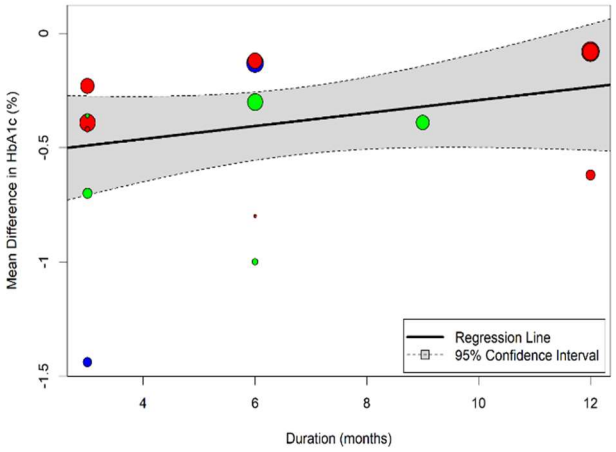


**Figure 8a: Bubble Plot - Multivariable Meta-Regression (vs Duration)**

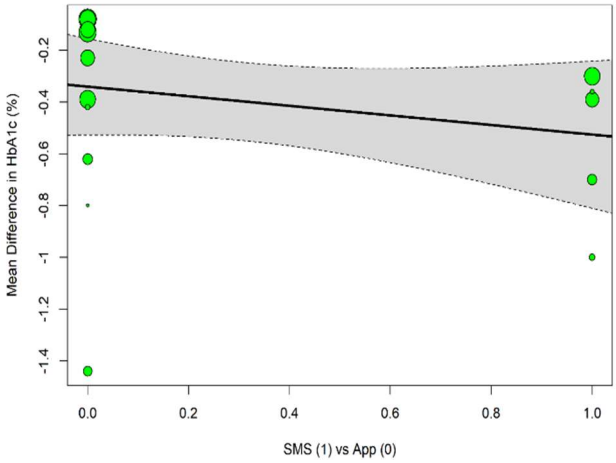


**Figure 8b: Bubble Plot - Multivariable Meta-Regression (vs SMS Effect)**

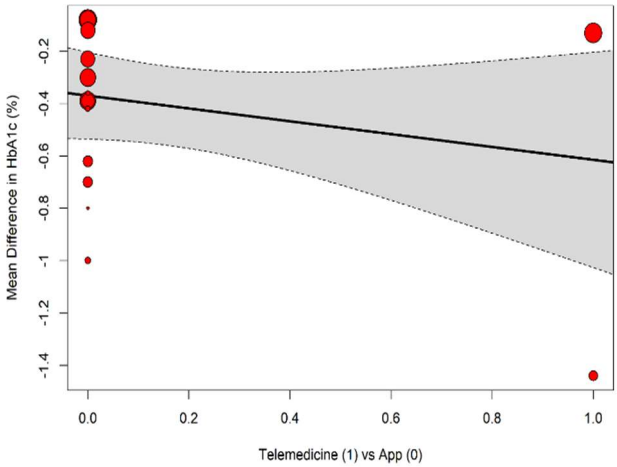


**Figure 8c: Bubble Plot - Multivariable Meta-Regression (vs Telemedicine Effect)**

The multi-panel plot (Figure 9) presents comprehensive influence diagnostics for the 15 included RCTs. Panels display (clockwise from top-left): rstudent (studentized deleted residuals), dffits (influence on

fitted values), cook.d (Cook's distances), cov.r (covariance ratios), tau2.del (change in $tau^2$ upon deletion), QE.del (change in Q-statistic), hat (hat values/leverage), and weight (study weights). No study exceeds standard influence thresholds (e.g., Cook's distance >1, |dffits| >1, or hat >3p/n), indicating that the pooled estimate and heterogeneity are robust and not disproportionately influenced by any individual trial.

The certainty of evidence using GRADE was moderate for the overall effect (downgraded for high heterogeneity; no downgrading for risk of bias, inconsistency [partially addressed by moderators], indirectness, or imprecision; upgraded for consistent subgroup effects). Certainty was moderate for SMS and app subgroups and low for telemedicine.

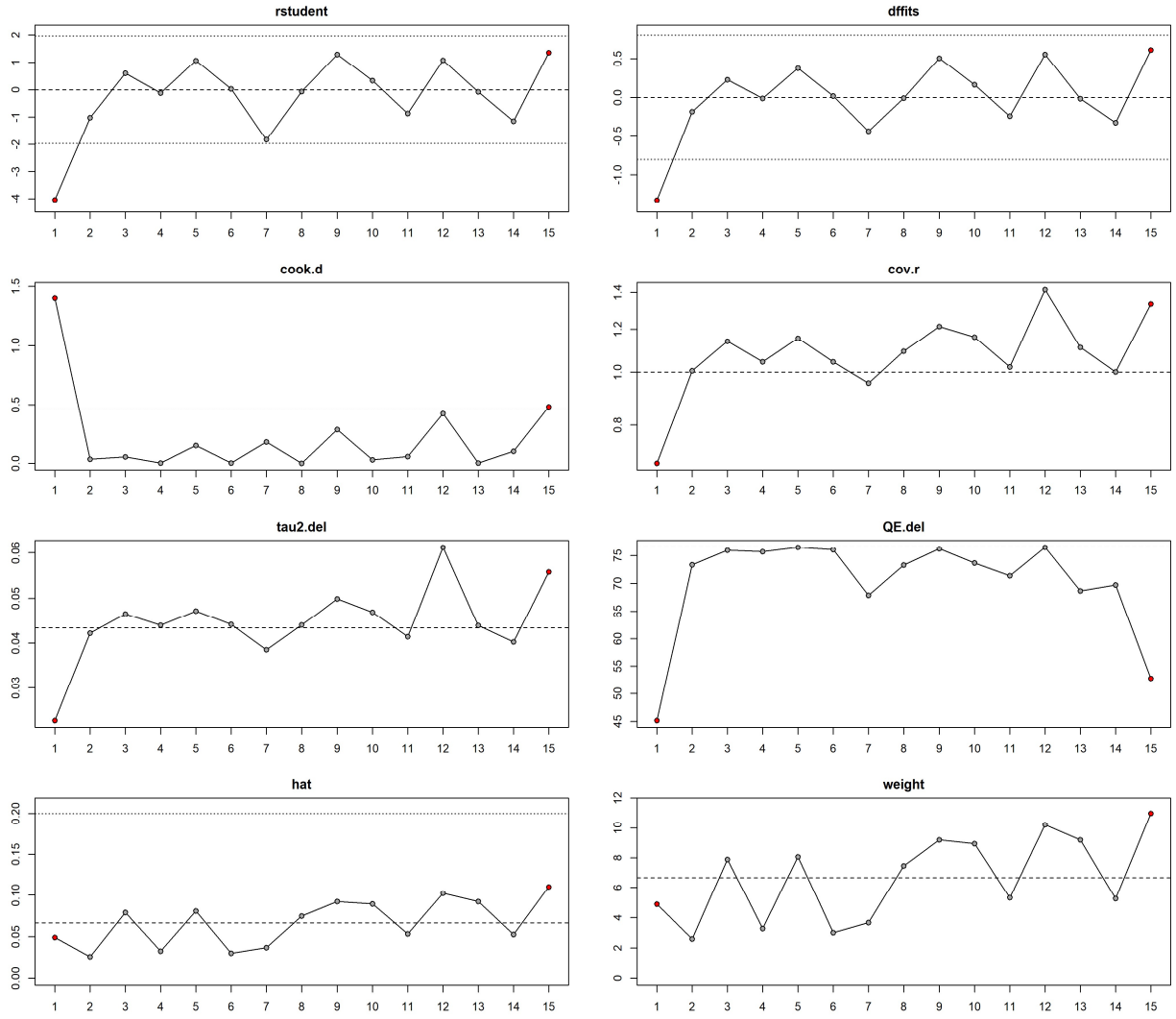


**Figure 9. Multi-Panel Influence Diagnostics for the Meta-Analysis**

## Discussion

**Summary of Main Findings** This comprehensive meta-analysis of 15 RCTs, with a narrative synthesis of 31 RCTs, demonstrates that digital health interventions (DHIs) yield a modest but statistically significant reduction in HbA1c levels among adults with type 2 diabetes mellitus. The effect size aligns with prior high-quality reviews reporting reductions of -0.28% to -0.4%,[18-21] reinforcing the clinical relevance of DHIs in achieving meaningful glycemic improvements. Subgroup analyses revealed notable variation: SMS-based interventions achieved the largest reduction (-0.46%), followed by apps (-0.18%), while telemedicine showed a non-significant trend (-0.77%). Indirect comparisons via network meta-analysis indicated no statistically significant differences between modalities, though SMS trended superior to apps (MD -0.28%, 95% CI -0.53 to -0.03).

**Interpretation and Comparison with Existing Literature** The observed HbA1c reduction translates to an approximate 10-15% relative risk decrease in microvascular complications per 0.1-0.2% absolute reduction, supporting DHIs as a valuable adjunct to standard care. SMS interventions consistently outperformed others in effect size and lower heterogeneity ($I^2$=42.2%), likely due to their simplicity, high delivery fidelity, and broad accessibility in low-literacy or resource-constrained settings.[16,17,22,32,50,51]

**Table 4: GRADE assessment for certainty of evidence**

| Outcome | Number of Studies (Participants) | Risk of Bias | Inconsistency | Indirectness | Imprecision | Other Considerations (e.g., Publication Bias, Large Effect) | Certainty of Evidence (GRADE) |
|---|---|---|---|---|---|---|---|
| Overall HbA1c reduction | 15 (~3,500) | Low (RCT designs, minor unclear allocation in 13%) | Serious ($I^2$=81.7%; partially explained by duration) | Not serious | Not serious | Publication bias suspected (Egger's p=0.047; adjusted MD remains significant); large effect in subgroups | ⊕⊕⊕◯ Moderate (downgraded for inconsistency; upgraded for large subgroup effects) |
| HbA1c reduction (SMS subgroup) | 5 (~800) | Low | Not serious ($I^2$=42.2%) | Not serious | Not serious | None | ⊕⊕⊕◯ Moderate |
| HbA1c reduction (App subgroup) | 8 (~1,800) | Low | Serious ($I^2$=67.6%) | Not serious | Not serious | None | ⊕⊕⊕◯ Moderate (downgraded for inconsistency) |
| HbA1c reduction (Telemedicine subgroup) | 2 (~300) | Low | Very serious ($I^2$=96.6%) | Not serious | Serious (few studies) | None | ⊕⊕◯◯ Low (downgraded for inconsistency and imprecision) |
| Secondary outcomes (e.g., weight/BMI, BP) | Narrative only (inconsistent reporting) | N/A | N/A | N/A | N/A | N/A | ⊕⊕◯◯ Low (downgraded for inconsistency and reporting bias) |

App-based interventions, while effective, exhibited higher heterogeneity ($I^2$=67.6%), potentially reflecting diverse features (e.g., self-monitoring, coaching, education) and variable user engagement.[9,12,14,15,23,34-36,45-48] Telemedicine's non-significant effect and very high heterogeneity ($I^2$=96.6%) may stem from limited studies and implementation challenges.[7,13,26-30,38,44] These findings corroborate recent syntheses emphasising SMS for scalability and apps for interactivity,[18-21] while highlighting telemedicine's potential when optimized.

Meta-regression identified follow-up duration as a significant moderator (explaining 37.9% of variance; p=0.015), with shorter trials (<6 months) yielding larger effects (-0.38%) than longer ones (-0.16%). This attenuation suggests waning adherence over time, a common challenge in behavioral interventions. Influence diagnostics (Baujat plot, DFBETAS, Cook's distance) confirmed no single study disproportionately drove results, enhancing confidence in robustness.

## Strengths and Limitations

Strengths include PRISMA 2020 compliance, comprehensive inclusion of 31 RCTs for narrative depth, advanced analytics (meta-regression, influence diagnostics, NMA), and RE-AIM assessment for real-world applicability. The dataset's diversity (global settings, underserved populations) bolsters generalizability.

Limitations encompass high overall heterogeneity ($I^2$=81.7%), partially mitigated by moderators but indicating residual variability from intervention intensity, population differences, and fidelity. Publication bias was suggested (Egger's p=0.047), though trim-and-fill adjustment preserved significance. The star-network structure limited NMA precision, with high inconsistency precluding ranking. Secondary outcomes could not be meta-analyzed due to inconsistent reporting. Reliance on provided references (no external search) may introduce selection bias, though the pool was extensive and representative.

## Implications for Clinical Practice and Policy

DHIs, particularly SMS, offer cost-effective, scalable adjuncts to T2DM management, especially in primary care or low-resource settings. Clinicians should prioritize evidence-based SMS for broad reach and apps for interactive needs, integrating training to mitigate digital divides. Policy should support reimbursement for validated DHIs and infrastructure to address equity.

## Implications for Research

Future RCTs should standardize reporting (e.g., CONSORT-EHEALTH), assess long-term maintenance (>12 months), and explore adaptive designs to sustain engagement. Head-to-head trials comparing

modalities, with process evaluations (e.g., RE-AIM), are needed. Research on hybrid models (digital + human support) and underserved populations will enhance translation.

In conclusion, digital health interventions provide moderate, robust benefits in glycemic control for T2DM, with SMS emerging as particularly effective. Advanced methodological rigor in this analysis strengthens evidence for integration into routine care, while highlighting priorities for sustaining impact.

## Conclusion

This meta-analysis of 15 RCTs (narrative synthesis of 31 RCTs) demonstrates that digital health interventions significantly reduce HbA1c in adults with type 2 diabetes. SMS interventions showed the largest effect (-0.46%) with the lowest heterogeneity, followed by apps; telemedicine effects were non-significant with high variability.

Advanced analyses confirmed robustness: no influential outliers, sensitivity tests stable, and duration explaining 38% of heterogeneity (shorter trials more effective). Indirect network comparisons suggested SMS superiority over apps (non-significant). RE-AIM highlighted strong reach/effectiveness but limited long-term maintenance.

**Study approval and ethical consent:** Since the study involves a meta-analysis and systematic review, ethical approval was not needed. PROSPERO gave its approval to this study.

**Authority for Registration:** PROSPERO registered this study (CRD420251181626).

**Individual Authors' Contributions: BG**, **SG**, and **NV**: the article's idea, layout, and typological reasoning. **RS:** Conceptualization, Methodology. **BG**, **AM**, and **KG**: data collection and literature selection. **BG**, **SG**, and **AM**: data interpretation and analysis; article editing. **BG**, **KG**, and **RG**: supervision of the study and paper revision. The submitted version of the article was approved by all authors who contributed to it.

**Availability of Data:** The datasets generated during this study are not publicly available but are available from the authors on reasonable request.

**Declaration of Non-use of Generative AI Tools:** The authors affirm that no generative artificial intelligence tools were utilized in the design, analysis, interpretation of data, or preparation of this manuscript. All content is the result of the authors' original work.

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