



Effectiveness of Lifestyle Modifications on Blood Sugar Control in Type 2 Diabetes Mellitus Patients : A Systematic Review

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ABSTRACT

Introduction: Type 2 Diabetes Mellitus (T2DM) is a progressive metabolic disorder associated with significant morbidity and healthcare costs. While pharmacological treatments are central, there is growing interest in lifestyle modifications as adjunct or primary interventions. However, the comparative effectiveness of different lifestyle components and the consistency of their glycemic benefits remain unclear.

Methods: This systematic review synthesized evidence from 80 studies (including RCTs, etc) identified through systematic screening of abstracts and full texts. Inclusion criteria required adult T2DM populations (≥ 18 years), lifestyle interventions (diet, exercise, behavioral support, education, or digital tools), and blood glucose outcomes (HbA1c, fasting plasma glucose, postprandial glucose). Data extraction focused on lifestyle intervention details,

study population
characteristics, glycemic
outcomes, secondary
cardiometabolic
outcomes, and study
design.

Results: Across the corpus, multicomponent lifestyle interventions produced pooled HbA1c reductions of approximately -0.51% to -0.63% compared to usual care. Exercise interventions, particularly supervised combined aerobic and resistance training, reduced HbA1c by -0.34% to -0.53% , with combined training showing superiority over either modality alone. Dietary interventions (Mediterranean, DASH, low-carbohydrate) achieved HbA1c reductions ranging from -0.39% to -0.82% ; however, long-term low-carbohydrate diets (≥ 12 months) showed non-significant effects (SMD -0.11 , $p=0.32$). Diabetes self-management education (DSME) in group formats reduced HbA1c by -0.44% to -0.87% over 6–24 months, while individual education showed benefit only in those with baseline HbA1c $>8\%$. Digital interventions (mobile apps, SMS) reduced HbA1c by -0.40% to -0.53% , with healthcare professional feedback as a key moderator. Yoga produced consistent improvements (HbA1c MD -0.47%). Intensive lifestyle interventions achieved diabetes remission in 7–12% of participants. Secondary benefits included weight loss, blood pressure reduction, improved lipids, and reduced medication requirements.

Discussion: The heterogeneous effect sizes across studies are systematically explained by three interacting mechanisms: baseline glycemic status (individuals with HbA1c $\geq 8\%$ show twice the benefit), intervention intensity (supervised, high-frequency,

and multicomponent programs produce larger effects), and sustainability (benefits attenuate beyond 12 months without ongoing contact). Weight loss is an important mediator but not the sole pathway; direct improvements in skeletal muscle glucose uptake, reduced postprandial carbohydrate load, and enhanced

insulin sensitivity contribute independently. Specific recommendations are derived for clinically relevant subgroups.

Conclusion: Lifestyle modifications significantly improve blood sugar control in T2DM, with clinically meaningful effects that are comparable to some pharmacological add-on therapies. The greatest benefits occur in patients with higher baseline HbA1c ($\geq 8\%$) receiving intensive, multicomponent, and supervised interventions. Future clinical practice should prioritize combined diet-plus-exercise programs, group-based DSME with ongoing contact, and targeted digital tools with provider feedback.

Keywords: Type 2 diabetes mellitus, lifestyle modification, glycemic control, HbA1c, exercise, dietary intervention, self-management education, systematic review.

INTRODUCTION

Background

Type 2 Diabetes Mellitus (T2DM) is a chronic metabolic disorder characterized by progressive insulin resistance and beta-cell dysfunction, affecting over 450 million adults worldwide (García-Molina et al., 2019). The global burden of T2DM continues to rise, driven by increasing rates of obesity, physical inactivity, and population aging (O'Donoghue et al., 2021). Poor glycemic control is directly linked to microvascular complications (retinopathy, nephropathy, neuropathy) and macrovascular events (myocardial infarction, stroke), making effective glucose management a clinical priority (Abrar et al., 2025).

Pharmacological treatments, including metformin, sulfonylureas, GLP-1 agonists, and insulin, form the cornerstone of T2DM management (Bolen et al., 2014). However, medication adherence is often suboptimal, side effects limit tolerability, and costs restrict access in low-resource settings (Butayeva et al., 2023). Consequently, there has been a paradigm shift toward incorporating lifestyle modifications—dietary changes, physical activity, weight management, and behavioral education—as either adjunctive or primary interventions for glycemic control (Schwingshackl et al., 2014).

The biological plausibility of lifestyle interventions is well-established. Regular physical activity increases skeletal muscle glucose uptake, improves insulin sensitivity, and enhances mitochondrial oxidative capacity (Pan et al., 2018). Dietary modifications, particularly reduced carbohydrate intake and adoption of Mediterranean or DASH dietary patterns, lower postprandial glucose excursions and reduce hepatic gluconeogenesis (Church et al., 2010). Behavioral support and diabetes self-management education (DSME) empower patients to sustain these changes over time (Esposito et al., 2009). Despite this mechanistic understanding, the magnitude of glycemic benefit—and which specific lifestyle components are most effective—remains debated (Schwingshackl et al., 2018).

Research Gap

Although numerous systematic reviews and meta-analyses have examined individual lifestyle interventions, several critical gaps persist. First, most existing syntheses focus on a single intervention type (e.g., diet-only or exercise-only), limiting comparisons across modalities (Azadbakht et al., 2010; Ichikawa et al., 2024). Second, the literature reports highly variable effect sizes, ranging from non-significant reductions to HbA1c decreases exceeding 2%, without a unified framework explaining this heterogeneity (Steinsbekk et al., 2012). Third, the long-term sustainability of lifestyle-induced glycemic improvements (beyond 12 months) is inconsistently reported (Odgers-Jewell et al., 2017). Fourth, specific population subgroups—such as patients with very poor baseline control (HbA1c >9%), newly diagnosed individuals, and those from low- and middle-income countries (LMICs)—have received insufficient attention in aggregated analyses (Kebede et al., 2018). Fifth, the comparative effectiveness of digital versus face-to-face delivery models has only recently emerged as a question requiring systematic synthesis (Arambepola et al., 2016).

Novelty

This systematic review offers several novel contributions. First, it provides a comprehensive synthesis across all major lifestyle domains (diet, exercise, education, digital, yoga, multicomponent) within a single analytic framework. Second, it systematically extracts and presents moderator variables—baseline HbA1c, intervention intensity, delivery format, supervision, and duration—to explain heterogeneous findings rather than simply reporting pooled estimates. Third, it includes recently published studies (up to 2025) that capture the rapidly evolving evidence on digital health tools and long-term dietary patterns (Hou et al., 2016; Duke et al., 2009). Fourth, it separately analyzes outcomes for clinically relevant subgroups: poorly controlled (HbA1c $\geq 8\%$) versus near-target patients, newly diagnosed versus longstanding diabetes, and high-income versus LMIC settings. Fifth, it synthesizes evidence on diabetes remission as a distinct outcome measure, which represents a paradigm shift from glycemic control to disease modification (Cradock et al., 2017).

Objectives

The primary objective of this systematic review is to evaluate the effectiveness of lifestyle modifications on blood sugar control in adults with T2DM. Secondary objectives include: (1) comparing the relative efficacy of different lifestyle components (diet alone, exercise alone, combined diet-exercise, DSME, digital interventions, yoga); (2) identifying key moderators (baseline HbA1c, intervention intensity, supervision, duration, delivery format) that influence treatment effects; (3) assessing secondary cardiometabolic outcomes (weight, blood pressure, lipids, medication requirements); (4) evaluating the durability of glycemic improvements beyond 12 months; (5) examining effectiveness in specific populations (LMICs, migrants, psychiatric comorbidity); and (6) quantifying the proportion of patients achieving diabetes remission with intensive lifestyle intervention.

Benefits of the Research

This research provides direct benefits for multiple stakeholders. For **clinicians**, the synthesized evidence offers clear, actionable guidance on which lifestyle interventions to prescribe for different patient profiles. For **patients**, the findings support shared decision-making regarding lifestyle change as an effective, low-risk adjunct to pharmacotherapy. For **policymakers**, the demonstrated effectiveness in LMICs and among migrants supports investment in community-based lifestyle programs. For **researchers**, the identified moderators and heterogeneity sources inform the design of future randomized controlled trials and the selection of appropriate comparator groups.

Hypotheses

Based on the existing literature, we tested the following hypotheses: (1) Multicomponent lifestyle interventions (diet + exercise + education) produce larger HbA1c reductions than single-component interventions. (2) Supervised exercise programs, particularly combined aerobic and resistance training, achieve superior glycemic outcomes compared to unsupervised or single-modality exercise. (3) Higher baseline HbA1c is associated with larger absolute treatment effects. (4) The glycemic benefit of lifestyle modifications attenuates over time, with smaller effect sizes at ≥ 12 months compared to ≤ 6 months. (5) Digital interventions with healthcare professional feedback are more effective than automated or unidirectional digital tools. (6) Lifestyle interventions produce

clinically meaningful secondary benefits beyond glycemic control, including weight loss, blood pressure reduction, and decreased medication requirements.

METHODS

Protocol

The study strictly adhered to the Preferred Reporting Items for Systematic Review and Meta-Analysis (PRISMA) 2020 guidelines to ensure methodological rigor and accuracy. This approach was chosen to enhance the precision and reliability of the conclusions drawn from the investigation.

Criteria for Eligibility

This systematic review aims to evaluate the Effectiveness of Lifestyle Modifications on Blood Sugar Control in Type 2 Diabetes Mellitus Patients.

Search Strategy

The keywords used for this research based PICO :

PICO Component	Keyword 1	Keyword 2	Keyword 3	Keyword 4
Population	Type 2 Diabetes Mellitus	Adults (≥ 18 years)	T2DM Patients	Overweight/Obese with T2DM
Intervention	Lifestyle Modifications	Dietary Changes	Physical Activity/Exercise	Behavioral Interventions
Comparison	Standard Care	Usual Care	No Intervention	Alternative Lifestyle Programs
Outcome	Blood Sugar Control	HbA1c Reduction	Fasting Plasma Glucose	Diabetes Remission

The Boolean MeSH keywords inputted on databases for this research are: ("*Type 2 Diabetes Mellitus*" OR "*Adults (≥ 18 years)*" OR "*T2DM Patients*" OR "*Overweight/Obese with T2DM*") AND ("*Lifestyle Modifications*" OR "*Dietary Changes*" OR "*Physical Activity/Exercise*" OR "*Behavioral*")

Interventions") AND ("Standard Care" OR "Usual Care" OR "No Intervention" OR "Alternative Lifestyle Programs") AND ("Blood Sugar Control" OR "HbA1c Reduction" OR "Fasting Plasma Glucose" OR "Diabetes Remission")

Screening

Abstract screening

We screened in sources based on their abstracts that met these criteria:

- **Population - Age and Diabetes Type:** Does the study include adults (≥ 18 years) diagnosed with Type 2 Diabetes Mellitus?
- **Intervention Type:** Does the intervention involve lifestyle modifications including dietary changes, physical activity/exercise programs, weight management, or behavioral interventions?
- **Outcome Measures:** Does the study measure blood glucose control outcomes such as HbA1c, fasting plasma glucose, postprandial glucose, or glucose tolerance measures?
- **Study Design:** Is the study design a randomized controlled trial, quasi-experimental study, cohort study, before-after study, systematic review, or meta-analysis?
- **Comparison Groups:** Does the study include appropriate comparison groups (control, usual care, baseline measurements, or alternative interventions)?
- **Non-Pharmacological Focus:** Does the study include lifestyle modification components (not solely pharmacological interventions)?
- **Diabetes Type Specificity:** Is the study population limited to Type 2 diabetes (excluding Type 1 diabetes, gestational diabetes, or secondary diabetes as primary focus)?
- **Publication Type:** Is the publication a full research study (not a case report, case series, editorial, or conference abstract only)?

Papers that failed any strict criterion were automatically excluded. For the remaining papers, we considered all screening questions together and made a holistic judgement about whether to screen in each paper.

Full-text screening

We then screened papers based on their full text using these additional criteria:

- **Population - Age and Diabetes Type:** Does the study include adults (≥ 18 years) diagnosed with Type 2 Diabetes Mellitus?
- **Intervention Type:** Does the intervention involve lifestyle modifications including dietary changes, physical activity/exercise programs, weight management, or behavioral interventions?
- **Outcome Measures:** Does the study measure blood glucose control outcomes such as HbA1c, fasting plasma glucose, postprandial glucose, or glucose tolerance measures?
- **Study Design:** Is the study design a randomized controlled trial, etc?
- **Comparison Groups:** Does the study include appropriate comparison groups (control, usual care, baseline measurements, or alternative interventions)?
- **Non-Pharmacological Focus:** Does the study include lifestyle modification components (not solely pharmacological interventions)?
- **Diabetes Type Specificity:** Is the study population limited to Type 2 diabetes (excluding Type 1 diabetes, gestational diabetes, or secondary diabetes as primary focus)?
- **Publication Type:** Is the publication a full research study (not a case report, case series, editorial, or conference abstract only)?

Papers that failed any strict criterion were automatically excluded. For the remaining papers, we considered all screening questions together and made a holistic judgement about whether to include each paper in the final analysis.

Data extraction

- **Lifestyle Interventions:**

Extract comprehensive details about all lifestyle modification interventions tested for blood sugar control in Type 2 diabetes patients, including:

- Type of lifestyle modifications (diet, exercise, education, counseling, behavioral therapy, etc.)
- Specific intervention components and content
- Intensity/frequency of each component
- Duration of intervention
- Delivery method (individual, group, digital, etc.)
- Who delivered the intervention
- Theoretical framework or model used (if specified)

- **Study Population:**

Extract characteristics of Type 2 diabetes mellitus patients in the study, including:

- Sample size
- Age (mean/range)
- Gender distribution
- Diabetes duration
- Baseline HbA1c or blood glucose levels
- BMI/weight status

- Medication use (insulin, oral medications)
- Comorbidities relevant to diabetes
- Exclusion criteria that might affect generalizability

- **Control/Comparison:**

Extract details about what the lifestyle modification interventions were compared against for blood sugar control effectiveness, including:

- Type of control/comparison group (usual care, standard treatment, waitlist, active control, etc.)
- Description of control group activities or treatments
- Whether control group received any lifestyle components
- Co-interventions received by both groups (medications, standard care)

- **Blood Sugar Outcomes:**

Extract all blood sugar control outcomes and effectiveness results for Type 2 diabetes patients, including:

- Primary blood sugar measures (HbA1c, fasting plasma glucose, postprandial glucose, etc.)
- Measurement methods and timing
- Baseline values for intervention and control groups
- Post-intervention values or change scores
- Effect sizes with confidence intervals

- Statistical significance (p-values)
- Clinical significance or target achievement rates

- **Study Design:**

Extract study design and methodological details relevant to assessing effectiveness of lifestyle modifications in Type 2 diabetes, including:

- Study design type (RCT, etc.)
- Randomization method (if applicable)
- Blinding procedures
- Follow-up duration and time points
- Setting (clinic, community, hospital, etc.)
- Country/region
- Attrition/dropout rates and reasons

- **Secondary Diabetes Outcomes:**

Extract all secondary diabetes-related outcomes affected by lifestyle modifications, including:

- Lipid profile changes (cholesterol, triglycerides, HDL, LDL)
- Blood pressure changes
- Weight/BMI changes
- Quality of life measures
- Diabetes complications or symptoms

- Medication changes or requirements
- Exercise tolerance or fitness measures
- Patient-reported outcomes related to diabetes management

- **Key Findings:**

Extract the study's main conclusions about effectiveness of lifestyle modifications on blood sugar control in Type 2 diabetes patients, including:

- Authors' interpretation of blood sugar control effectiveness
- Magnitude of effect described by authors
- Which lifestyle components were most effective (if analyzed)
- Factors that influenced effectiveness
- Clinical recommendations made by authors
- Sustainability or long-term effects noted

Table 1. Article Search Strategy

Database	Keywords	Hits
Pubmed	<i>("Type 2 Diabetes Mellitus" OR "Adults (≥18 years)" OR "T2DM Patients" OR "Overweight/Obese with T2DM") AND ("Lifestyle Modifications" OR "Dietary Changes" OR "Physical Activity/Exercise" OR "Behavioral Interventions") AND ("Standard Care" OR "Usual Care" OR "No Intervention" OR "Alternative Lifestyle Programs") AND ("Blood Sugar Control" OR "HbA1c</i>	2

	<i>Reduction" OR "Fasting Plasma Glucose" OR "Diabetes Remission")</i>	
Semantic Scholar	<i>("Type 2 Diabetes Mellitus" OR "Adults (≥18 years)" OR "T2DM Patients" OR "Overweight/Obese with T2DM") AND ("Lifestyle Modifications" OR "Dietary Changes" OR "Physical Activity/Exercise" OR "Behavioral Interventions") AND ("Standard Care" OR "Usual Care" OR "No Intervention" OR "Alternative Lifestyle Programs") AND ("Blood Sugar Control" OR "HbA1c Reduction" OR "Fasting Plasma Glucose" OR "Diabetes Remission")</i>	250
Springer	<i>("Type 2 Diabetes Mellitus" OR "Adults (≥18 years)" OR "T2DM Patients" OR "Overweight/Obese with T2DM") AND ("Lifestyle Modifications" OR "Dietary Changes" OR "Physical Activity/Exercise" OR "Behavioral Interventions") AND ("Standard Care" OR "Usual Care" OR "No Intervention" OR "Alternative Lifestyle Programs") AND ("Blood Sugar Control" OR "HbA1c Reduction" OR "Fasting Plasma Glucose" OR "Diabetes Remission")</i>	309
Google Scholar	<i>("Type 2 Diabetes Mellitus" OR "Adults (≥18 years)" OR "T2DM Patients" OR "Overweight/Obese with T2DM") AND ("Lifestyle Modifications" OR "Dietary Changes" OR "Physical Activity/Exercise" OR "Behavioral Interventions") AND ("Standard Care" OR "Usual Care" OR "No Intervention" OR "Alternative Lifestyle Programs") AND ("Blood Sugar Control" OR "HbA1c Reduction" OR "Fasting Plasma Glucose" OR "Diabetes Remission")</i>	9,670
Wiley Online Library	<i>("Type 2 Diabetes Mellitus" OR "Adults (≥18 years)" OR "T2DM Patients" OR "Overweight/Obese with T2DM") AND ("Lifestyle Modifications" OR "Dietary Changes" OR "Physical Activity/Exercise" OR "Behavioral Interventions") AND ("Standard Care" OR "Usual Care" OR "No Intervention" OR "Alternative Lifestyle Programs") AND ("Blood Sugar Control" OR "HbA1c Reduction" OR "Fasting Plasma Glucose" OR "Diabetes Remission")</i>	287

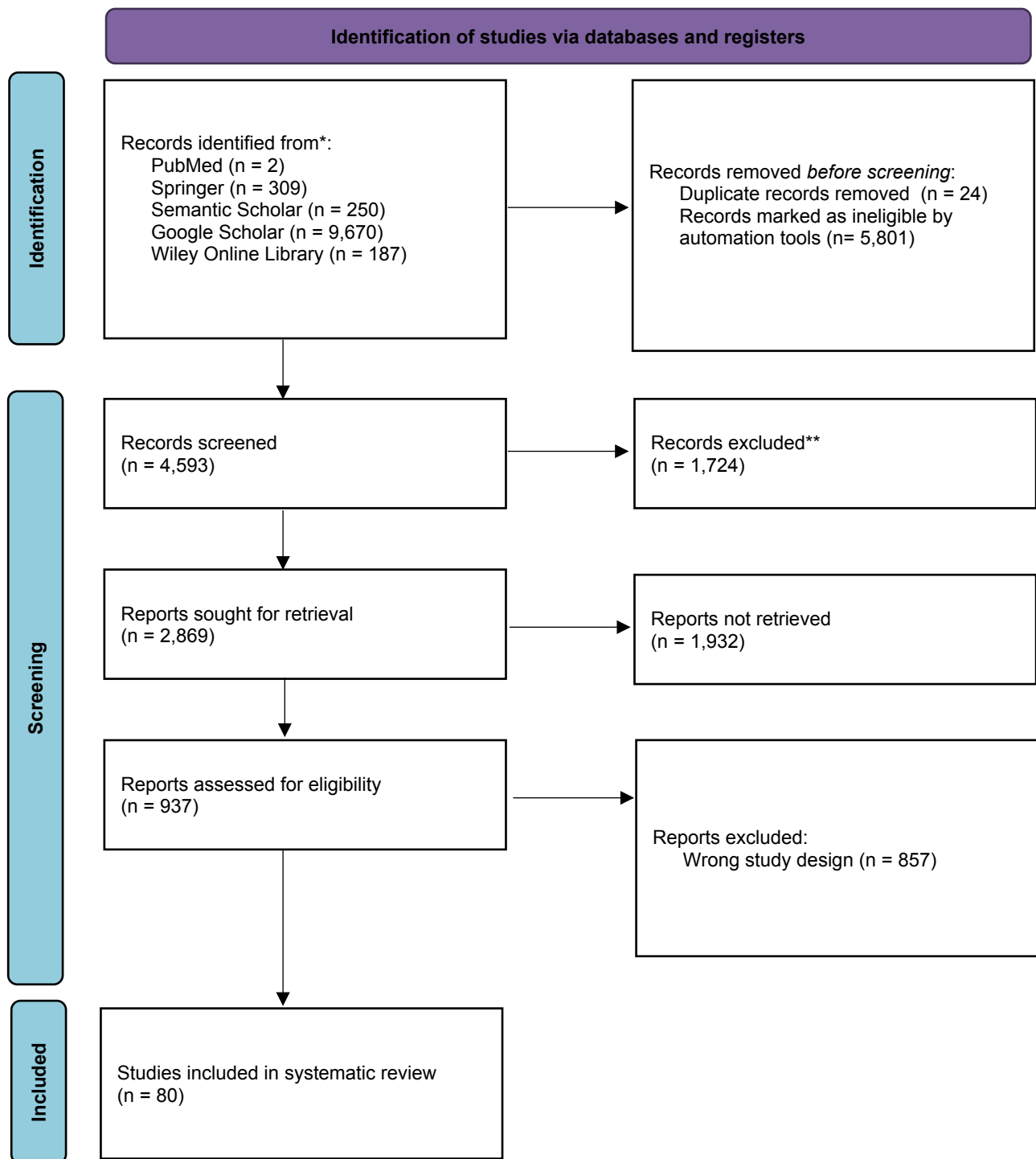


Figure 1. Article search flowchart

Risk of Bias

Study	Selection Bias	Performance Bias	Detection Bias	Attrition Bias	Reporting Bias	Overall Risk
Girija Kumari et al., 2018 [26]	Moderate	Moderate	Low	Moderate	Low	Moderate
F. Megahed et al., 2021 [27]	Moderate	Moderate	Low	Unclear	Low	Moderate
S. Abrar et al., 2025 [3]	Low	Low	Low	Low	Low	Low
Yating Zhang et al., 2022 [22]	Low	Low	Low	Low	Low	Low
L. García-Molina et al., 2019 [1]	Low	Low	Low	Low	Low	Low
Nandita Sanghani et al., 2013 [28]	Moderate	Moderate	Low	Moderate	Low	Moderate
A. Mitra et al., 2012 [29]	Low	Moderate	Low	Low	Low	Low
G. O'Donoghue et al., 2021 [2]	Low	Low	Low	Low	Low	Low
Liang Chen et al., 2015 [30]	Low	Low	Low	Low	Low	Low
R. Wing, 2010 [20]	Low	Low	Low	Low	Low	Low

Study	Selection Bias	Performance Bias	Detection Bias	Attrition Bias	Reporting Bias	Overall Risk
Alexander P. Cotter et al., 2014 [31]	Low	Moderate	Moderate	Moderate	Low	Moderate
M. Franz et al., 2015 [23]	Low	Low	Low	Low	Low	Low
X. Pi-Sunyer et al., 2007 [32]	Low	Low	Low	Low	Low	Low
R. Pamungkas et al., 2017 [33]	Moderate	Moderate	Moderate	Moderate	Low	Moderate
L. Avery et al., 2012 [34]	Low	Low	Low	Low	Low	Low
Kate Odgers-Jewell et al., 2017 [14]	Low	Low	Low	Low	Low	Low
A. Bhosale & Poovishnu Devi Thangavelu, 2019 [35]	Moderate	Moderate	Low	Moderate	Low	Moderate
S. Z. A. Shah et al., 2021 [36]	Low	Low	Low	Low	Low	Low
Jessica	Low	Low	Low	Low	Low	Low

Study	Selection Bias	Performance Bias	Detection Bias	Attrition Bias	Reporting Bias	Overall Risk
Amerkamp et al., 2024 [37]						
Kevin A. Cradock et al., 2017 [19]	Low	Low	Low	Low	Low	Low
C. Terranova et al., 2015 [38]	Low	Low	Low	Low	Low	Low
Andi Sulfikar et al., 2023 [39]	Moderate	Moderate	Moderate	Moderate	Low	Moderate
A. Steinsbekk et al., 2012 [13]	Low	Low	Low	Low	Low	Low
K. Esposito et al., 2009 [9]	Low	Moderate	Low	Low	Low	Low
C. Hou et al., 2016 [17]	Low	Low	Low	Low	Low	Low
Y. Meng et al., 2017 [40]	Low	Low	Low	Low	Low	Low
Mingxuan Cui et al., 2016 [41]	Low	Low	Low	Low	Low	Low
S. Duke et al., 2009 [18]	Low	Low	Low	Low	Low	Low

Study	Selection Bias	Performance Bias	Detection Bias	Attrition Bias	Reporting Bias	Overall Risk
Joni L. Strom & L. Egede, 2012 [42]	Moderate	Moderate	Moderate	Unclear	Moderate	Moderate
L. Schwingshackl et al., 2014 [6]	Low	Low	Low	Low	Low	Low
E. Westman et al., 2008 [25]	Low	Moderate	Low	Low	Low	Low
E. Heinrich et al., 2010 [43]	Moderate	Moderate	Moderate	Moderate	Low	Moderate
C. Arambepola et al., 2016 [16]	Low	Low	Low	Low	Low	Low
Charlene C. Quinn et al., 2011 [44]	Low	Moderate	Low	Low	Low	Low
Yuli Kurniawati et al., 2020 [45]	Moderate	Moderate	Moderate	Moderate	Low	Moderate
Shakila Sabir et al., 2025 [46]	Low	Moderate	Low	Low	Low	Low
Bei Pan et al., 2018 [7]	Low	Low	Low	Low	Low	Low

Study	Selection Bias	Performance Bias	Detection Bias	Attrition Bias	Reporting Bias	Overall Risk
K. Esposito et al., 2015 [47]	Low	Low	Low	Low	Low	Low
Kiana Farahbod et al., 2024 [48]	Moderate	Moderate	Moderate	Unclear	Moderate	Moderate
Hani Andriyana et al., 2023 [49]	Moderate	Moderate	Moderate	Moderate	Low	Moderate
Xiaojie Yuan et al., 2020 [50]	Unclear	Unclear	Moderate	Moderate	Low	Unclear
A. Marume et al., 2025 [51]	Low	Low	Low	Low	Low	Low
Jamila Butayeva et al., 2023 [5]	Low	Low	Low	Low	Low	Low
F. Toledo et al., 2007 [24]	Unclear	Unclear	Moderate	Low	Low	Unclear
L. Schwingshackl et al., 2018 [10]	Low	Low	Low	Low	Low	Low
E. Mikhael et al., 2020 [52]	Low	Low	Low	Low	Low	Low
T. Church et al., 2010 [8]	Low	Low	Low	Low	Low	Low

Study	Selection Bias	Performance Bias	Detection Bias	Attrition Bias	Reporting Bias	Overall Risk
I. Salama et al., 2023 [53]	Moderate	Moderate	Low	Moderate	Low	Moderate
L. Azadbakht et al., 2010 [11]	Low	Moderate	Low	Low	Low	Low
Edward W. Gregg et al., 2012 [21]	Low	Low	Low	Low	Low	Low
Yasmiin Khoirul Bariyyah et al., 2021 [54]	Moderate	Moderate	Low	Moderate	Low	Moderate
D. Cox et al., 2020 [55]	Low	Moderate	Low	Low	Low	Low
Anna M. Chudyk & R. Petrella, 2011 [56]	Moderate	Moderate	Low	Moderate	Low	Moderate
J. van Dijk et al., 2013 [57]	Low	Moderate	Low	Low	Low	Low
Sarah Pousinho et al., 2016 [58]	Low	Low	Low	Low	Low	Low
D. Thomas et al., 2006 [59]	Low	Low	Low	Low	Low	Low

Study	Selection Bias	Performance Bias	Detection Bias	Attrition Bias	Reporting Bias	Overall Risk
S. S. A. Al Harbi et al., 2022 [60]	Low	Low	Low	Low	Low	Low
Ç. Şahin et al., 2019 [61]	Low	Low	Low	Low	Low	Low
H. Thind et al., 2017 [62]	Low	Low	Low	Low	Low	Low
Y. Yokoyama et al., 2014 [63]	Low	Low	Low	Low	Low	Low
Ammal M. Metwally et al., 2019 [64]	Unclear	Unclear	Moderate	Moderate	Low	Unclear
Girija Kumari et al., 2021 [65]	Moderate	Moderate	Low	Moderate	Low	Moderate
Bo Wang et al., 2020 [66]	Moderate	Moderate	Low	Moderate	Low	Moderate
S. Balducci et al., 2010 [67]	Low	Low	Low	Low	Low	Low
N. Mishra, 2014 [68]	Moderate	Moderate	Low	Moderate	Low	Moderate
K. Innes & Terry	Low	Moderate	Low	Low	Low	Low

Study	Selection Bias	Performance Bias	Detection Bias	Attrition Bias	Reporting Bias	Overall Risk
Kit Selfe, 2015 [69]						
Harpreet Kour et al., 2019 [70]	Low	Moderate	Low	Low	Low	Low
S. Bolen et al., 2014 [4]	Low	Low	Low	Low	Low	Low
Adriana Cimo et al., 2012 [71]	Moderate	Unclear	Moderate	Moderate	Low	Moderate
Kaifeng Liu et al., 2019 [72]	Low	Low	Low	Low	Low	Low
Irma Rizqia Khoiruni et al., 2023 [73]	Moderate	Moderate	Low	Moderate	Low	Moderate
R. Huntriss et al., 2018 [74]	Low	Low	Low	Low	Low	Low
Aimee Afable & Nidhi Shree Karingula, 2016 [75]	Moderate	Moderate	Moderate	Moderate	Low	Moderate
Lee-Wen Pai et al., 2016 [76]	Low	Low	Low	Low	Low	Low

Study	Selection Bias	Performance Bias	Detection Bias	Attrition Bias	Reporting Bias	Overall Risk
Lal B. Rawal et al., 2021 [77]	Low	Low	Low	Low	Low	Low
Mihiretu M Kebede et al., 2018 [15]	Low	Low	Low	Low	Low	Low
Ramavtar Sharma et al., 2019 [78]	Moderate	Moderate	Low	Moderate	Low	Moderate
Takahiro Ichikawa et al., 2024 [12]	Low	Low	Low	Low	Low	Low
Shanshan Chen et al., 2022 [79]	Low	Low	Low	Low	Low	Low
Celia Cruz-Cobo & M. J. Santicano, 2020 [80]	Low	Low	Low	Low	Low	Low

RESULTS

Characteristics of Included Studies

Study	Country/Region	Setting	Sample Size	Intervention Focus
Girija Kumari et al., 2018 [26]	India (New Delhi)	Diabetes research center outpatient	224 [26]	Multicomponent lifestyle counseling (LIHM)
F. Megahed et al., 2021 [27]	Egypt (Ismailia)	University hospital outpatient clinics	92 [27]	Lifestyle modification (diet, PA, DSME)
S. Abrar et al., 2025 [3]	Multinational	Multiple	>20,000 (meta-analysis) [3]	Lifestyle and pharmacological interventions
Yating Zhang et al., 2022 [22]	UK, USA, Italy, India, Denmark, Australia	Multiple	3,997 [22]	Lifestyle interventions for diabetes remission
L. García-Molina et al., 2019 [1]	Americas, Europe, Asia, Africa	Primary care and hospital	Varied (28 RCTs) [1]	Dietary/lifestyle interventions
Nandita Sanghani et al.,	India (Ahmedabad)	Hospital outpatient	279 [28]	Structured vs unstructured exercise

Study	Country/Region	Setting	Sample Size	Intervention Focus
2013 [28]				
A. Mitra et al., 2012 [29]	India (West Midnapore)	Hospital	60 [29]	Dietary + physical activity lifestyle intervention
G. O'Donoghue et al., 2021 [2]	LMICs (multinational)	Hospital/clinic and community	16,670 [2]	Lifestyle interventions in LMICs
Liang Chen et al., 2015 [30]	Multinational	Multiple	Varied (16 RCTs) [30]	Comprehensive lifestyle change (diet, exercise, education)
R. Wing, 2010 [20]	United States	Outpatient clinical	5,145 [20]	Intensive lifestyle intervention (ILI) vs education
Alexander P. Cotter et al., 2014 [31]	United States and international	Web/digital	Varied (9 studies) [31]	Internet-based lifestyle interventions
M. Franz et al., 2015 [23]	Multinational	Multiple	6,754 [23]	Lifestyle weight-loss interventions
X. Pi-Sunyer et	United States	16 clinical	5,145 [32]	Intensive lifestyle vs diabetes

Study	Country/Region	Setting	Sample Size	Intervention Focus
al., 2007 [32]		centers		support/education
R. Pamungkas et al., 2017 [33]	Predominantly Western countries	Primary care and community	Varied (23 studies) [33]	Family-supported DSME
L. Avery et al., 2012 [34]	Europe, Australia, North America, Asia	Clinical and community	1,975 [34]	Behavioral interventions for physical activity
Kate Odgers-Jewell et al., 2017 [14]	USA (38%), UK (13%), Italy (11%), others	Predominantly primary care	8,533 [14]	Group-based self-management education
A. Bhosale & Poovishnu Devi Thangavelu, 2019 [35]	India	Clinical/hospital	64 [35]	Lifestyle modification + conventional physiotherapy
S. Z. A. Shah et al., 2021 [36]	Multinational	Multiple	2,140 [36]	Exercise/physical activity interventions
Jessica Amerkamp et al., 2024 [37]	Multinational	Multiple	599 [37]	Combined diet-and-exercise interventions

Study	Country/Region	Setting	Sample Size	Intervention Focus
Kevin A. Cradock et al., 2017 [19]	Multinational	Predominantly clinical	Varied (13 RCTs) [19]	Combined diet and physical activity (BCT analysis)
C. Terranova et al., 2015 [38]	Multinational	Multiple	Varied (10 studies) [38]	Lifestyle-based weight-loss interventions
Andi Sulfikar et al., 2023 [39]	Not specified	Multiple	6,169 total [39]	Health coaching interventions
A. Steinsbekk et al., 2012 [13]	USA, UK, Sweden, Austria, Mexico, Thailand, Spain, Netherlands, Italy	Primary care and hospital diabetes centers	2,833 [13]	Group-based DSME vs routine care
K. Esposito et al., 2009 [9]	Italy (Naples)	Diabetes clinic research center	215 [9]	Mediterranean-style vs low-fat diet
C. Hou et al., 2016 [17]	Europe (4), USA (3), Asia (2), Africa (1)	Outpatient/community	851 [17]	Mobile phone apps for diabetes self-management
Y. Meng et al., 2017 [40]	Multinational	Multiple	734 [40]	Low-carbohydrate diets

Study	Country/Region	Setting	Sample Size	Intervention Focus
Mingxuan Cui et al., 2016 [41]	USA, Canada, Korea, Spain, Norway, Netherlands, Finland, UK	Community/ambulatory	1,022 [41]	Smartphone app-based self-management
S. Duke et al., 2009 [18]	Australia, USA, others	Clinical/community	1,359 [18]	Individual face-to-face diabetes education
Joni L. Strom & L. Egede, 2012 [42]	United States	Multiple	12–3,535 per study [42]	Social support interventions
L. Schwingshackl et al., 2014 [6]	Multinational	Supervised training settings	915 [6]	Exercise training modalities (AET, RT, CT)
E. Westman et al., 2008 [25]	United States	Outpatient research clinic	84 analyzed [25]	Low-carbohydrate ketogenic vs low-glycemic index diet
E. Heinrich et al., 2010 [43]	North America, UK, Sweden, South Korea, Thailand	Multiple	Mean 127/study [43]	Multicomponent self-management interventions

Study	Country/Region	Setting	Sample Size	Intervention Focus
C. Arambepola et al., 2016 [16]	HIC and LMIC (mixed)	Community/healthcare	1,155 [16]	Automated brief message interventions
Charlene C. Quinn et al., 2011 [44]	United States	Community primary care	163 [44]	Mobile phone personalized behavioral coaching
Yuli Kurniawati et al., 2020 [45]	International	Multiple	Varied (14 studies) [45]	Physical exercise for glycemic control
Shakila Sabir et al., 2025 [46]	Pakistan (Kahuta, Faisalabad)	Community-based (THQ hospitals)	100 [46]	Lifestyle medicine vs standard medical care
Bei Pan et al., 2018 [7]	Canada, Korea, Japan, Turkey, Iran, India, Brazil, Australia, others	Multiple	2,208 [7]	Exercise training modalities comparison
K. Esposito et al., 2015 [47]	Multinational	Multiple	4,937 across 56 trials [47]	Mediterranean diet for T2DM
Kiana Farahbod et al.,	Multinational (Spain, China,	Multiple	Varied (23–24	Dietary interventions and

Study	Country/Region	Setting	Sample Size	Intervention Focus
2024 [48]	Japan, others)		studies) [48]	gut microbiota in T2DM
Hani Andriyana et al., 2023 [49]	Not specified	Multiple	Varied	mHealth for glycemic control and adherence
Xiaojie Yuan et al., 2020 [50]	Australia, USA, Canada, Spain, Italy, Kuwait	Multiple	567 [50]	Ketogenic diet in T2DM
A. Marume et al., 2025 [51]	USA, Spain, Austria, China, Brazil, Denmark, England, Japan, Korea, Taiwan, Canada	Community and health facilities	12–327 per study [51]	Dietary interventions and glycemic control
Jamila Butayeva et al., 2023 [5]	USA, England, Sweden, Brazil, China, Ethiopia, Nigeria, Vietnam	Hospital, outpatient, community	3,556 [5]	Health literacy-driven self-management education
F. Toledo et al., 2007 [24]	United States (Pittsburgh)	University clinical	10 [24]	Exercise and weight loss (mechanistic study)

Study	Country/Region	Setting	Sample Size	Intervention Focus
		research center		
L. Schwingshackl et al., 2018 [10]	North America, Europe, Asia, Australia/New Zealand	Multiple	4,937 [10]	Dietary approaches comparison (9 patterns)
E. Mikhael et al., 2020 [52]	Iran, Turkey, UAE, Jordan, Qatar	Outpatient (Middle East)	1,971 [52]	DSME in Middle East countries
T. Church et al., 2010 [8]	United States (Louisiana)	Exercise laboratory/clinical research center	262 [8]	Aerobic, resistance, or combined exercise vs control
I. Salama et al., 2023 [53]	Egypt (Cairo, NRC)	Employee health/outpatient	184 [53]	Multicomponent lifestyle modification program
L. Azadbakht et al., 2010 [11]	Iran (Isfahan)	Hospital	31 [11]	DASH diet vs control diet
Edward W. Gregg et al., 2012 [21]	United States	Multicenter clinical	4,503 [21]	Intensive lifestyle intervention (remission outcomes)

Study	Country/Region	Setting	Sample Size	Intervention Focus
Yasmiin Khoirul Bariyyah et al., 2021 [54]	International	Multiple	Varied (40 studies) [54]	Aerobic exercise and blood glucose
D. Cox et al., 2020 [55]	United States (Virginia)	University medical center	30 [55]	Glycemic Excursion Minimization with CGM
Anna M. Chudyk & R. Petrella, 2011 [56]	Multiple	Multiple	Varied (34 studies) [56]	Aerobic and resistance exercise on CV risk factors
J. van Dijk et al., 2013 [57]	Netherlands (Maastricht)	Laboratory/clinical	20 [57]	Activities of daily living vs moderate-intensity exercise
Sarah Pousinho et al., 2016 [58]	Multinational (North America, Europe, Asia, Africa, Australia)	Community pharmacy, primary care, hospital	5,761 [58]	Pharmacist-led interventions including lifestyle counseling
D. Thomas et al., 2006 [59]	Multinational	Multiple	377 [59]	Exercise for type 2 diabetes

Study	Country/Region	Setting	Sample Size	Intervention Focus
S. S. A. Al Harbi et al., 2022 [60]	USA, Qatar, Denmark, Netherlands, Iran, Philippines, China	Multiple	2,346 [60]	Group self-management education vs standard care
Ç. Şahin et al., 2019 [61]	Mixed HIC and LMIC	Healthcare/community (digital)	1,328 [61]	Tailored mobile text messaging
H. Thind et al., 2017 [62]	India (18/23), England, Iran, Indonesia, Cuba	Clinical and community	2,473 [62]	Yoga for T2DM
Y. Yokoyama et al., 2014 [63]	USA, Czech Republic, Brazil	Multiple	255 [63]	Vegetarian/vegan diets
Ammal M. Metwally et al., 2019 [64]	Egypt (rural village)	Community-based	205 [64]	Lifestyle health education program
Girija Kumari et al., 2021 [65]	India (New Delhi)	Hospital outpatient (DDRC)	224 [65]	Lifestyle Intervention Holistic (LIH) Model counseling
Bo Wang et al.,	China (Shandong)	Rural villages	120 [66]	Real-life lifestyle interventions (meal order,

Study	Country/Region	Setting	Sample Size	Intervention Focus
2020 [66]	province)			PA, breathing)
S. Balducci et al., 2010 [67]	Italy	22 outpatient diabetes clinics	606 [67]	Intensive supervised exercise + counseling vs counseling only
N. Mishra, 2014 [68]	India	Hospital/clinic	67 [68]	Yogic exercise and diet vs antidiabetic therapy
K. Innes & Terry Kit Selfe, 2015 [69]	India (80%), UK, Cuba, Iran	Clinical and community	2,170 [69]	Yoga-based programs
Harpreet Kour et al., 2019 [70]	India	Hospital/medical college	148 [70]	Structured exercise therapy in newly diagnosed T2DM
S. Bolen et al., 2014 [4]	USA (48%), Europe (32%), others	Primary care, diabetes clinic, home/remote	33,124 [4]	Patient activation interventions
Adriana Cimo et al., 2012 [71]	United States	Inpatient psychiatric and community mental health	Varied (4 studies) [71]	Lifestyle DSME for T2DM with schizophrenia

Study	Country/Region	Setting	Sample Size	Intervention Focus
Kaifeng Liu et al., 2019 [72]	North America (48%), Europe (26%), Asia (19%), Africa (7%)	Multiple	Median 75/trial [72]	Mobile app-assisted self-care
Irma Rizqia Khoiruni et al., 2023 [73]	Indonesia (Lumajang)	Clinical and community	30 [73]	Diet modification training
R. Huntriss et al., 2018 [74]	Multinational	Multiple	2,204 [74]	Low-carbohydrate diets
Aimee Afable & Nidhi Shree Karingula, 2016 [75]	LMICs (20 countries)	Multiple	Varied (66 studies) [75]	Lifestyle interventions in LMICs
Lee-Wen Pai et al., 2016 [76]	USA, UK, India, Denmark, Italy, Korea, China, Taiwan, Australia, Japan, Thailand	Hospital outpatient and community	915 [76]	Leisure-time physical activities
Lal B. Rawal et al., 2021 [77]	USA (13), UK (2), Spain, Netherlands	Community and health	5,018 [77]	Lifestyle interventions for migrants/ethnic minorities

Study	Country/Region	Setting	Sample Size	Intervention Focus
		facility		
Mihiretu M Kebede et al., 2018 [15]	USA, South Korea, Norway, China, Canada, others	Outpatient/community (eHealth)	3,787 [15]	Digital interventions for poorly controlled T2DM
Ramavtar Sharma et al., 2019 [78]	India (Gaya, Bihar)	Community health centers and district hospital	3,044 analyzed [78]	Ayurveda + yoga + lifestyle vs lifestyle + allopathy
Takahiro Ichikawa et al., 2024 [12]	Israel, USA, Australia, Taiwan, Sweden	Clinical/research	524 [12]	Long-term low-carbohydrate diets (≥ 12 months)
Shanshan Chen et al., 2022 [79]	Predominantly India	Multiple	1,335 [79]	Yoga for uncomplicated T2DM
Celia Cruz-Cobo & M. J. Santi-Cano, 2020 [80]	USA, Spain, Brazil, UK, Belgium, Sweden, Greece, Qatar, South Africa, Australia	Predominantly primary care	6,602 [80]	Diabetes education in primary care

Effects of Lifestyle Modifications on Blood Sugar Control

Overview of Glycemic Outcomes

The following table consolidates the primary glycemic effect estimates reported across included studies.

Study	Outcome Measure	Baseline (Intervention / Control)	Post-Intervention Effect (Intervention / Control or Change)	Effect Size or Pooled Estimate	p-value / Statistical Significance	Notes
Girija Kumari et al., 2018 [26]	HbA1c (%), FBG (mg/dL), PPG (mg/dL)	HbA1c 9.3±1.5; FBG 175.5±32.3; PPG 275.5±61.3 [26]	HbA1c 8.4±1.3; FBG 144.7±17.6; PPG 199.0±48.3 [26]	Not reported	p<0.001 [26]	Quasi-experimental; no pooled CI
F. Megahed et al., 2021 [27]	HbA1c	Not reported numerically [27]	Significant improvement vs control [27]	Not reported	p<0.009 to <0.0001 [27]	Quasi-experimental; only direction reported
S. Abrar et al., 2025 [3]	HbA1c (%)	Not reported [3]	Lifestyle vs standard care: MD -0.61%	MD -0.61% (95% CI	p<0.001; I ² =48% [3]	Lifestyle + pharma adds further

Study	Outcome Measure	Baseline (Intervention / Control)	Post-Intervention Effect (Intervention / Control or Change)	Effect Size or Pooled Estimate	p-value / Statistical Significance	Notes
			[3]	−0.79 to −0.43) [3]		−0.32% (95% CI −0.51 to −0.13) [3]
S. Abrar et al., 2025 [3]	FBG (mmol/L)	Not reported [3]	MD −0.41 mmol/L [3]	MD −0.41 mmol/L (95% CI −0.55 to −0.28) [3]	p<0.001; I ² =42% [3]	Same meta-analysis
Yating Zhang et al., 2022 [22]	Diabetes remission (OR)	—	OR 6.09 at ≤12 months [22]	OR 6.09 (95% CI 3.14 to 11.79) [22]	Significant [22]	Also: weight MD ~−7 kg vs control [22]
L. García-Molina et al., 2019 [1]	HbA1c (%)	Multiple baselines by trial [1]	WMD −0.51% [1]	WMD −0.51% (95% CI −0.67 to −0.35) [1]	p=0.000; I ² =91.7% [1]	With DSME: −0.71%; without DSME:

Study	Outcome Measure	Baseline (Intervention / Control)	Post-Intervention Effect (Intervention / Control or Change)	Effect Size or Pooled Estimate	p-value / Statistical Significance	Notes
						-0.24% [1]
Nandita Sanghani et al., 2013 [28]	HbA1c (%)	Structured 7.65±0.66% ; Unstructured 7.43±0.56% ; Control 7.59±0.56% [28]	Structured -0.59% ; Unstructured -0.14% ; Control +0.10% [28]	Not reported	Structured p=0.030 ; Unstructured p=0.120 [28]	In high-HbA1c subgroup (>7%): structured -0.77% (p<0.01), unstructured -0.48% (p=0.04) [28]
A. Mitra et al., 2012 [29]	HbA1c (%), FPG (mg/dL), PPG (mg/dL)	HbA1c 8.3±0.58; FPG 223±9.23; PPG 295±12.3	HbA1c 6.3±0.32; FPG 145±2.52; PPG 174±2.59 [29]	Not reported	Significant [29]	1 - y e a r RCT; large absolute changes

Study	Outcome Measure	Baseline (Intervention / Control)	Post-Intervention Effect (Intervention / Control or Change)	Effect Size or Pooled Estimate	p-value / Statistical Significance	Notes
		[29]				
G. O'Donoghue et al., 2021 [2]	HbA1c (%)	Not reported pooled [2]	MD -0.63% [2]	MD -0.63% (95% CI -0.86 to -0.40) [2]	Significant (CI excludes 0) [2]	LMICs only; FBG SMD -0.35 (95% CI -0.54 to -0.16) [2]
Liang Chen et al., 2015 [30]	HbA1c (change, SMD)	Not reported pooled [30]	SMD -0.37 [30]	SMD -0.37 (95% CI -0.59 to -0.14) [30]	p=0.001; I ² =93.72% [30]	16 RCTs; ≥6 months duration
R. Wing, 2010 [20]	HbA1c (%)	ILI 47% at target (<7%) vs DSE 45% [20]	ILI -0.36% vs DSE -0.09% (avg 4 yrs) [20]	Difference -0.27% (95% CI -0.40 to -0.33 for ILI; -0.13 to -0.06 for	p<0.0001 [20]	Year 1: 72% ILI vs 50% DSE at HbA1c <7% [20]

Study	Outcome Measure	Baseline (Intervention / Control)	Post-Intervention Effect (Intervention / Control or Change)	Effect Size or Pooled Estimate	p-value / Statistical Significance	Notes
				DSE) [20]		
Alexander P. Cotter et al., 2014 [31]	HbA1c	Varied by study [31]	2/7 studies showed significant between-group improvement [31]	Carter 2011: -2.18% vs -0.9% (p<0.05) [31]	Mixed; Noh 2010 within-group -1.53% (p=0.03) [31]	Web-based interventions; inconsistent glycemic effects
M. Franz et al., 2015 [23]	HbA1c (%)	Varied: ~7.3%–8.8% [23]	<5% weight loss: -0.2% (NS); Mediterranean + ≥5% loss: -1.2% (p<0.0001); ILI + ≥5% loss: -0.6% (p<0.0001)	<5%: 95% CI -0.6 to +0.2, p=0.28 [23]	Mediterranean p<0.0001; ILI p<0.0001 [23]	Weight loss >5% necessary for HbA1c benefit [23]

Study	Outcome Measure	Baseline (Intervention / Control)	Post-Intervention Effect (Intervention / Control or Change)	Effect Size or Pooled Estimate	p-value / Statistical Significance	Notes
			[23]			
X. Pi-Sunyer et al., 2007 [32]	HbA1c (%); FBG (mg/dL)	HbA1c: ILI 7.25%; DSE 7.29%; FBG: ILI 152; DSE 154 [32]	HbA1c: ILI 6.61%; DSE 7.15%; FBG: ILI -21.5; DSE -7.2 [32]	HbA1c between-group diff -0.50%; FBG -14.3 mg/dL [32]	p<0.001 for both [32]	72.7% ILI vs 50.8% DSE achieved HbA1c <7% [32]
R. Pamungkas et al., 2017 [33]	HbA1c	Not reported numerically [33]	Up to ~1% reduction in studies showing benefit [33]	Not pooled [33]	10/23 studies significant [33]	Family-supported DSME; qualitative synthesis
L. Avery et al., 2012 [34]	HbA1c (%)	Not reported [34]	WMD -0.32% [34]	WMD -0.32% (95% CI -0.44 to -0.21) [34]	Significant [34]	Physical activity behavioral interventions; sustained

Study	Outcome Measure	Baseline (Intervention / Control)	Post-Intervention Effect (Intervention / Control or Change)	Effect Size or Pooled Estimate	p-value / Statistical Significance	Notes
						24 months
Kate Odgers-Jewell et al., 2017 [14]	HbA1c (%)	Mean ~8.3% both groups [14]	MD -0.34% at primary point [14]	MD -0.34% (95% CI -0.51 to -0.17) [14]	p<0.0001 [14]	36–48 months: MD -0.93% (95% CI -1.52 to -0.34) [14]
A. Bhosale & Poovishnu Devi Thangavelu, 2019 [35]	HbA1c	Not reported numerically [35]	Extremely significant reduction in LSM group [35]	Not reported	p<0.0001 intergroup; p<0.0001 within LSM group [35]	3 - m o n t h quasi-experimenta l
S. Z. A. Shah et al., 2021 [36]	HbA1c; FBG	Not pooled numerically [36]	Both significantly improved [36]	HbA1c: p<0.0001; FBG:	p<0.0001; I ² =81% [36]	32 RCTs; exercise intervention

Study	Outcome Measure	Baseline (Intervention / Control)	Post-Intervention Effect (Intervention / Control or Change)	Effect Size or Pooled Estimate	p-value / Statistical Significance	Notes
				p=0.03 [36]		s
Jessica Amerkamp et al., 2024 [37]	HbA1c; FBG; fasting insulin	Not reported numerically [37]	Adding exercise to diet infrequently improved glycemia vs diet alone [37]	Not pooled [37]	Mixed; mostly NS [37]	Combined diet+exercise RCTs; fitness improvements consistent
Kevin A. Cradock et al., 2017 [19]	HbA1c (%)	8.03% (intervention); 8.00% (control) [19]	-1.11% at 3 months; -0.67% at 6 months; -0.28% at 12 months; -0.26% at 24 months [19]	Overall -0.53% (95% CI -0.74 to -0.32) [19]	p<0.00001 overall; 12-month p=0.03 [19]	Combined diet + PA; effect wanes beyond 6 months
C. Terranova	HbA1c (%)	Mean 7.9% [38]	MD -0.29% (overall NS)	95% CI -0.61 to	p=0.07 (NS); sensitivity	Weight-loss focused;

Study	Outcome Measure	Baseline (Intervention / Control)	Post-Intervention Effect (Intervention / Control or Change)	Effect Size or Pooled Estimate	p-value / Statistical Significance	Notes
et al., 2015 [38]			[38]	0.03; p=0.07 [38]	using Look AHEAD 1-yr: -0.38% (p significant) [38]	modest non-significant overall pooled effect
Andi Sulfikar et al., 2023 [39]	HbA1c; FBG	Not reported [39]	Consistently significant HbA1c decreases across HC modalities [39]	Not pooled [39]	"Significant" qualitatively [39]	Health coaching; qualitative synthesis only
A. Steinsbekk et al., 2012 [13]	HbA1c (%); FBG (mmol/L)	8.31% (IG); 8.16% (CG) [13]	HbA1c: -0.44% at 6 mo; -0.46% at 12 mo; -0.87% at 2	1 2 - m o : 95% CI -0.74 to -0.18, p=0.001; 2-yr: 95% CI	p=0.0006 (6 mo); p=0.001 (12 mo); p<0.00001	FBG -1.26 mmol/L at 12 months (p<0.00001) [13]

Study	Outcome Measure	Baseline (Intervention / Control)	Post-Intervention Effect (Intervention / Control or Change)	Effect Size or Pooled Estimate	p-value / Statistical Significance	Notes
			yr [13]	−1.25 to −0.49 [13]	(2 yr) [13]	
K. Esposito et al., 2009 [9]	HbA1c (%); FBG (mmol/L); Time to antihyperglycemic drug	HbA1c ~7.75% (MED); ~7.71% (LF) [9]	Year 1: MED −1.2% vs LF −0.6% (diff −0.6%) [9]	HR drug initiation: 0.63 (95% CI 0.51–0.86) [9]	log-rank p=0.001; annual differences p<0.05 [9]	4 - year RCT; 44% vs 70% needed drugs by year 4 [9]
C. Hou et al., 2016 [17]	HbA1c (%)	Study-level means ~6.7–8.5% [17]	Mean reduction 0.49% vs control [17]	0.49% (95% CI 0.30 to 0.68) [17]	p<0.001; I ² =10% [17]	Mobile apps; HCP feedback subgroup: 0.56% [17]
Y. Meng et al., 2017 [40]	HbA1c (%); FBG (mmol/L)	Not reported [40]	HbA1c: WMD −0.44%; FBG: WMD	HbA1c: 95% CI −0.61 to −0.26,	HbA1c p=0.00; FBG p=0.84 [40]	Low-carbohydrate diet; 9 RCTs

Study	Outcome Measure	Baseline (Intervention / Control)	Post-Intervention Effect (Intervention / Control or Change)	Effect Size or Pooled Estimate	p-value / Statistical Significance	Notes
			−0.05 mmol/L (NS) [40]	p=0.00 [40]		
Mingxuan Cui et al., 2016 [41]	HbA1c (%)	Baseline <8% and >8% subgroups [41]	MD −0.40% overall [41]	MD −0.40% (95% CI −0.69 to −0.11); I ² =77% [41]	p=0.007 [41]	Smartphone apps; without feedback: NS [41]
S. Duke et al., 2009 [18]	HbA1c (%)	~6.6–12.2% across studies [18]	WMD −0.1% overall (NS); baseline HbA1c >8%: WMD −0.3% (significant) [18]	Overall 95% CI −0.3 to 0.1, p=0.33 [18]	Overall NS; high-HbA1c subgroup p=0.007 [18]	Individual education; no benefit overall; benefit in poor controllers
Joni L. Strom & L. Egede,	HbA1c	Not specified numerically	Higher social support associated	Not pooled [42]	Not specified [42]	Qualitative systematic review

Study	Outcome Measure	Baseline (Intervention / Control)	Post-Intervention Effect (Intervention / Control or Change)	Effect Size or Pooled Estimate	p-value / Statistical Significance	Notes
2012 [42]		[42]	with improved HbA1c [42]			
L. Schwingshackl et al., 2014 [6]	HbA1c (%); FBG (mmol/L)	Not specified [6]	CT vs RT: MD -0.62% HbA1c; CT vs AET: MD -0.17%; AET vs RT: MD -0.20% [6]	CT vs RT: 95% CI -0.95 to -0.30, p=0.0002 [6]	AET vs RT p=0.0007; CT vs AET p=0.02 [6]	Network meta-analysis; combined training best
E. Westman et al., 2008 [25]	HbA1c (%); FBG (mg/dL)	LCKD: 8.8±1.8%; LGID: 8.3±1.9% [25]	LCKD -1.5% vs LGID -0.5% [25]	Between-group p=0.03 [25]	p=0.03 [25]	95.2% LCKD vs 62.1% LGID reduced/eliminated meds [25]
E. Heinrich et al., 2010	HbA1c	Not reported	5/13 RCTs showed lower	Not pooled [43]	Significant in 5/13 [43]	Group programs

Study	Outcome Measure	Baseline (Intervention / Control)	Post-Intervention Effect (Intervention / Control or Change)	Effect Size or Pooled Estimate	p-value / Statistical Significance	Notes
[43]		numerically [43]	post-intervention HbA1c; ES 0.26–1.25 [43]			with practice component most promising
C. Arambepola et al., 2016 [16]	HbA1c (%)	Not reported [16]	MD -0.53% [16]	MD -0.53% (95% CI -0.59 to -0.47); I ² =0% [16]	Significant (CI excludes 0) [16]	Automated messaging; BMI MD -0.25 (NS) [16]
Charlene C. Quinn et al., 2011 [44]	HbA1c (%)	Intervention ~9.9%; Control ~9.2% [44]	Intervention -1.9%; Control -0.7% [44]	Between-group difference -1.2% [44]	p=0.001 [44]	Mobile behavioral coaching; 12-month cluster-RCT
Yuli Kurniawati	HbA1c; Blood	Not reported	Significant reductions	Not pooled [45]	"Significant" qualitatively	Aerobic and combined

Study	Outcome Measure	Baseline (Intervention / Control)	Post-Intervention Effect (Intervention / Control or Change)	Effect Size or Pooled Estimate	p-value / Statistical Significance	Notes
et al., 2020 [45]	glucose	numerically [45]	qualitatively reported across studies [45]		[45]	exercise; 14 studies
Shakila Sabir et al., 2025 [46]	HbA1c (%); FBG (mg/dL); PPG (mmol/L)	Group A: HbA1c 10.60; FBG 363.24; PPG 9.54. Group B: HbA1c 10.99; FBG 382.34; PPG 9.77 [46]	Group A: 7.82; 195.40; 6.94. Group B: 8.16; 222.20; 7.22 [46]	Not reported as CIs [46]	p<0.001 [46]	12-week RCT; lifestyle vs standard care
Bei Pan et al., 2018 [7]	HbA1c (%); FBG (mg/dL)	Not reported [7]	Combined vs no exercise: -0.53%; Supervised	Combined 95% CI -0.68 to	Significant for all supervised modalities	Network meta-analysis; supervised

Study	Outcome Measure	Baseline (Intervention / Control)	Post-Intervention Effect (Intervention / Control or Change)	Effect Size or Pooled Estimate	p-value / Statistical Significance	Notes
			aerobic vs no exercise: -0.30%; Supervised resistance vs no exercise: -0.30% [7]	-0.45 [7]	[7]	> unsupervised by ~0.60% [7]
K. Esposito et al., 2015 [47]	HbA1c (%); FBG (mg/dL)	Not reported [47]	HbA1c MD -0.47% (de novo meta-analysis) [47]	95% CI -0.56 to -0.38; I ² =3.5% [47]	Significant [47]	Mediterranean diet; FBG ~13 mg/dL greater than control [47]
Kiana Farahbod et al., 2024 [48]	HbA1c; FBG; insulin	Not reported numerically [48]	High-fiber diet, Mediterranean diet, LC diet, structured weight loss,	Not pooled [48]	Qualitative directions only [48]	Gut microbiota focus; 23–24 studies

Study	Outcome Measure	Baseline (Intervention / Control)	Post-Intervention Effect (Intervention / Control or Change)	Effect Size or Pooled Estimate	p-value / Statistical Significance	Notes
			vitamin K2: all significant improvements [48]			
Hani Andriyana et al., 2023 [49]	HbA1c; adherence	Not reported numerically [49]	HbA1c improved across mHealth modalities [49]	Not pooled [49]	"Effective" qualitatively [49]	mHealth systematic review; 2–13 month interventions
Xiaojie Yuan et al., 2020 [50]	FBG (mmol/L); HbA1c (%)	Not reported (within-subject pre-post) [50]	FBG −1.29 mmol/L; HbA1c −1.07% [50]	FBG: 95% CI −1.78 to −0.79; HbA1c: 95% CI −1.37 to −0.78 [50]	Significant (CI excludes 0) [50]	Ketogenic diet; pre-post only, no control arm
A. Marume	HbA1c (%)	Not	Overall MD	95% CI	p<0.0001	Intensive

Study	Outcome Measure	Baseline (Intervention / Control)	Post-Intervention Effect (Intervention / Control or Change)	Effect Size or Pooled Estimate	p-value / Statistical Significance	Notes
et al., 2025 [51]		reported pooled [51]	−0.30%; at 6 mo: −0.25%; at 12 mo: −0.35% [51]	−0.45 to −0.15; $I^2=93.4%$ [51]	[51]	lifestyle MD −0.25%; diet-only −0.17% [51]
Jamila Butayeva et al., 2023 [5]	HbA1c	Not reported pooled [5]	14/15 RCTs significant; largest reduction −3.4% in 3-month nurse-led hospital program [5]	Not pooled [5]	Significant in 14/15 RCTs [5]	HL-driven DSME; qualitative narrative
F. Toledo et al., 2007 [24]	HbA1c (%); FBG (mg/dL); 2-h OGTT glucose	HbA1c 7.85±0.52; FBG 164±15; 2-h	HbA1c 6.47±0.25; FBG 126±6; 2-h 205±15	No CIs; changes: HbA1c ~−1.4%, FBG ~−38,	p<0.01 for HbA1c and 2-h glucose; p<0.05 for	Single-arm; mechanistic study; no control

Study	Outcome Measure	Baseline (Intervention / Control)	Post-Intervention Effect (Intervention / Control or Change)	Effect Size or Pooled Estimate	p-value / Statistical Significance	Notes
	(mg/dL)	260±16 [24]	[24]	2-h ~-55 [24]	FBG [24]	
L. Schwingshackl et al., 2018 [10]	HbA1c (%); FBG (mmol/L)	Not reported [10]	All diets reduce HbA1c -0.47 to -0.82% vs control; FBG -1.00 to -1.61 mmol/L [10]	LC vs LF: -0.35% (95% CI -0.56 to -0.14); Med vs LF: -0.32% (95% CI -0.53 to -0.11) [10]	All pairwise diet vs control: significant [10]	Network meta-analysis; 9 diets; LC ranked best for HbA1c, Med best for FBG [10]
E. Mikhael et al., 2020 [52]	HbA1c (%); FBG (mg/dL); Non-fasting BG (mg/dL)	Varied by trial [52]	HbA1c absolute effect -1.05%; FBG -27 mg/dL; non-fasting BG -44	Not pooled as meta-analysis [52]	Significant in 8/10 for HbA1c; 6/6 for FBG; 3/3 for non-fasting [52]	Middle East DSME; pharmacist-led most effective

Study	Outcome Measure	Baseline (Intervention / Control)	Post-Intervention Effect (Intervention / Control or Change)	Effect Size or Pooled Estimate	p-value / Statistical Significance	Notes
			mg/dL [52]			
T. Church et al., 2010 [8]	HbA1c (%)	All groups ~7.56–7.62 % [8]	Combined –0.34% vs control; Aerobic –0.24% (NS); Resistance –0.16% (NS) [8]	Combined: 95% CI –0.64 to –0.03 [8]	Combined p=0.03; aerobic p=0.14; resistance p=0.32 [8]	9 - m o n t h RCT; only combined training significant overall
I. Salama et al., 2023 [53]	HbA1c (%); FBG	IG 7.9±1.7%; CG 8.2±1.9% [53]	IG: 6.9±1.4%; CG: 8.3±2.1% [53]	~1.0% absolute IG reduction vs no change in CG [53]	IG within-group p<0.0001; between-group p<0.05 [53]	6 - m o n t h quasi-experimental; Egypt
L. Azadbakht et al., 2010	FBG (mg/dL); HbA1c	FBG: Control 171.8;	FBG change: DASH –29.4 vs control	Not reported as between-	p=0.04 for both [11]	8 - w e e k crossover; DASH diet

Study	Outcome Measure	Baseline (Intervention / Control)	Post-Intervention Effect (Intervention / Control or Change)	Effect Size or Pooled Estimate	p-value / Statistical Significance	Notes
[11]	(A1C, %)	DASH 160.9; A1C: Control 7.9%; DASH 7.7% [11]	−12.8; A1C change: DASH −1.7% vs control −0.5% [11]	group CI [11]		
Edward W. Gregg et al., 2012 [21]	Diabetes remission (any)	HbA1c ~7.3–7.4% (both groups) [21]	ILI remission yr1: 11.5%; yr4: 7.3% vs DSE ~2.0% at both [21]	Prevalence ratio yr1: 5.8; yr4: 3.4 [21]	p<0.001 at each year [21]	Sustained ≥ 2 - y r remission: ILI 9.2% vs DSE 1.7% [21]
Yasmiin Khoirul Bariyyah et al., 2021 [54]	Blood glucose (mg/dL)	Varied by study [54]	39/40 studies showed significant reductions; e.g., walking: −9–13 mg/dL; aerobic	Not pooled [54]	97.5% studies significant [54]	Aerobic exercise; 40 studies

Study	Outcome Measure	Baseline (Intervention / Control)	Post-Intervention Effect (Intervention / Control or Change)	Effect Size or Pooled Estimate	p-value / Statistical Significance	Notes
			gymnastics: ~21–30 mg/dL [54]			
D. Cox et al., 2020 [55]	HbA1c (%)	GEMCGM ~8.9%; RC ~8.8% [55]	GEMCGM: 7.6%; RC: 8.7% [55]	Between-group ANCOVA F=5.57; difference ~1.11% [55]	p=0.03 [55]	CGM-assisted lifestyle program; also med reduction benefit [55]
Anna M. Chudyk & R. Petrella, 2011 [56]	HbA1c (%)	Not reported [56]	Aerobic: WMD -0.6%; Combined: WMD -0.67% [56]	Aerobic: 95% CI -0.98 to -0.27; Combined: 95% CI -0.93 to -0.40 [56]	Significant [56]	Resistance alone: NS for HbA1c

Study	Outcome Measure	Baseline (Intervention / Control)	Post-Intervention Effect (Intervention / Control or Change)	Effect Size or Pooled Estimate	p-value / Statistical Significance	Notes
J. van Dijk et al., 2013 [57]	2 4 - h glucose; time in hyperglycemia; postprandial glucose iAUC	Sedentary: 6h51min >10 mmol/L; avg 8.9 mmol/L [57]	Exercise: 4h47min (-34%); ADL: 6h02min (NS); Exercise avg: 8.1 mmol/L (-0.6 mmol/L) [57]	Exercise vs control p<0.001; ADL vs control p=0.67 (time in hyperglycemia) [57]	Exercise: p<0.001; ADL: p=0.92 (avg 2 4 - h glucose) [57]	Acute crossover; postprandial iAUC: exercise -35%, ADL -17% [57]
Sarah Pousinho et al., 2016 [58]	HbA1c (%); Blood glucose	Not reported pooled [58]	HbA1c: 24/26 studies favored intervention; diff -0.18% to -2.1% [58]	Not pooled as single estimate [58]	Several studies p<0.001 to p<0.05 [58]	Pharmacist-led; includes lifestyle counseling
D. Thomas et al., 2006	HbA1c (%)	Not reported	Decrease -0.6% [59]	95% CI -0.9 to -0.3	p<0.05 [59]	Exercise meta-analysis;

Study	Outcome Measure	Baseline (Intervention / Control)	Post-Intervention Effect (Intervention / Control or Change)	Effect Size or Pooled Estimate	p-value / Statistical Significance	Notes
[59]		[59]		[59]		visceral fat also reduced
S. S. A. Al Harbi et al., 2022 [60]	HbA1c (SMD); FBG (SMD)	Not reported numerically [60]	HbA1c SMD ≈ 0.25 (sensitivity: NS); FBG SMD ≈ 0.27 [60]	HbA1c: 95% CI 0.13–0.38; FBG: 95% CI 0.10–0.43 [60]	HbA1c $p < 0.001$; FBG $p = 0.002$ [60]	Group self-management education; HbA1c robust? Sensitivity shows not robust
Ç. Şahin et al., 2019 [61]	HbA1c (Hedges' g)	Baseline ~ 6.5 –8% [61]	$g = 0.54$ [61]	95% CI 0.08–0.99; $I^2 = 82.8\%$ [61]	$p < 0.001$ [61]	Tailored SMS; after trim-and-fill $g \approx 0.38$
H. Thind et al., 2017 [62]	HbA1c (d+); FBG (d+); PPBG	Not reported [62]	HbA1c $d+ = 0.36$; FBG $d+ = 0.58$;	HbA1c: 95% CI 0.16–0.56;	All significant [62]	Yoga; 23 studies; $I^2 = 64$ –69%

Study	Outcome Measure	Baseline (Intervention / Control)	Post-Intervention Effect (Intervention / Control or Change)	Effect Size or Pooled Estimate	p-value / Statistical Significance	Notes
	(d+)		PPBG d+=0.40 [62]	FBG: 95% CI 0.40–0.76; PPBG: 95% CI 0.23–0.56 [62]		
Y. Yokoyama et al., 2014 [63]	HbA1c (%); FBG (mmol/L)	Varied by study [63]	HbA1c MD –0.39%; FBG MD –0.36 mmol/L (NS) [63]	HbA1c: 95% CI –0.62 to –0.15, p=0.001; FBG: 95% CI –1.04 to 0.32, p=0.301 [63]	HbA1c significant; FBG NS [63]	Vegetarian diets; I ² =3% for HbA1c
Ammal M. Metwally	HbA1c (%)	11.33±2.02	8.45±2.46%	Absolute change	p<0.001 [64]	Single-arm; highly

Study	Outcome Measure	Baseline (Intervention / Control)	Post-Intervention Effect (Intervention / Control or Change)	Effect Size or Pooled Estimate	p-value / Statistical Significance	Notes
et al., 2019 [64]		% [64]	[64]	-2.88%; relative -25% [64]		elevated baseline; no control
Girija Kumari et al., 2021 [65]	HbA1c (%); FBG (mg/dL); PPG (mg/dL)	Eligibility thresholds: HbA1c >7 %, FBG >120, PPG >180 [65]	HbA1c: -0.97% within-LIC at 12 mo; ITT between-group -2.82% [65]	HbA1c ITT: 95% CI -5.26 to -0.37; PPG diff -70.16 mg/dL (95% CI -85.15 to -55.16) [65]	p<0.001 [65]	LIHM counseling; large PPG effect
Bo Wang et al., 2020 [66]	FBG (mmol/L); HbA1c (%)	FBG 11.22±2.78; HbA1c 8.94±1.92% [66]	FBG 8.40±1.81; HbA1c 8.06±1.32% [66]	Not reported as CIs [66]	p<0.001 [66]	3 - m o n t h quasi-experimentally; rural China

Study	Outcome Measure	Baseline (Intervention / Control)	Post-Intervention Effect (Intervention / Control or Change)	Effect Size or Pooled Estimate	p-value / Statistical Significance	Notes
S. Balducci et al., 2010 [67]	HbA1c (%); OGTT glucose iAUC; 2-h glucose	Overall ~6.7% (49.3 mmol/mol) [67]	HbA1c between-group: -0.30%; 2-h glucose: -1.81 mmol/L; glucose iAUC: -135.0 mmol/L×min [67]	HbA1c: 95% CI -0.49 to -0.10; iAUC: 95% CI -197.5 to -72.5 [67]	HbA1c p<0.001; iAUC p<0.001; 2-h p=0.021 [67]	IDES; supervised combined exercise; counseling-only comparator
N. Mishra, 2014 [68]	HbA1c; FBG	Group II (exercise+diet): HbA1c 0.551; Group III (meds): 0.61 [68]	HbA1c significantly lower in Group II vs Group III [68]	Not reported as CIs [68]	p<0.001 (Group III vs Group I) [68]	Quasi-experimental; yogic exercise + diet vs antidiabetic therapy
K. Innes &	HbA1c (%);	Varied by	FBG: MD	FBG: 95%	FBG	Yoga; 25

Study	Outcome Measure	Baseline (Intervention / Control)	Post-Intervention Effect (Intervention / Control or Change)	Effect Size or Pooled Estimate	p-value / Statistical Significance	Notes
Terry Kit Selfe, 2015 [69]	FBG (mg/dL); PPBG	study [69]	−25.56 mg/dL (RCT meta-analysis); HbA1c: MD −0.49% (95% CI −1.03 to 0.05; p=0.07) [69]	CI −39.60 to −11.53, p<0.01 [69]	significant; HbA1c borderline [69]	controlled trials; methodological heterogeneity
Harpreet Kour et al., 2019 [70]	HbA1c (%); FBG (mg/dL); PPBG (mg/dL)	FBG: Control 104.8; IG 106.1. HbA1c: Control 5.97%; IG 5.93% [70]	At 6 mo: FBG control 104.7 vs IG 89.9; HbA1c control 5.86% vs IG 5.14% [70]	Not reported as CIs [70]	All p<0.001 [70]	Newly diagnosed young adults; 6-month RCT
S. Bolen et al., 2014 [4]	HbA1c (WMD)	Weighted mean	WMD −0.37% [4]	95% CI −0.45 to −0.28;	Significant [4]	PAIs; 111 RCTs; 12,780

Study	Outcome Measure	Baseline (Intervention / Control)	Post-Intervention Effect (Intervention / Control or Change)	Effect Size or Pooled Estimate	p-value / Statistical Significance	Notes
		~8.1% [4]		I ² =83% [4]		participants
Adriana Cimo et al., 2012 [71]	FBG (mg/dL); HbA1c (%)	Lindenmayer: FBG 115.85; DART: HbA1c ~7.3–7.4% [71]	Lindenmayer: FBG 98.05 (–17.8 mg/dL; p<0.001); DART: HbA1c NS at 6 or 12 months [71]	Not reported as CIs [71]	Lindenmayer p<0.001; DART NS [71]	Schizophrenia comorbidity population; inpatient vs outpatient differences
Kaifeng Liu et al., 2019 [72]	HbA1c (SMD); FBG (SMD)	Not reported numerically [72]	HbA1c SMD –0.44 (MD ~–0.49%); FBG SMD –0.29 (MD ~–0.66 mmol/L) [72]	HbA1c: 95% CI –0.59 to –0.29, p<0.001; FBG: 95% CI –0.49 to –0.10, p=0.004	Both significant [72]	Mobile app-assisted self-care; 27 trials

Study	Outcome Measure	Baseline (Intervention / Control)	Post-Intervention Effect (Intervention / Control or Change)	Effect Size or Pooled Estimate	p-value / Statistical Significance	Notes
				[72]		
Irma Rizqia Khoiruni et al., 2023 [73]	Blood sugar levels	Not reported numerically [73]	Significant in intervention; not significant in control [73]	Not reported [73]	Intervention p=0.005; Control p=0.317 [73]	30-participant quasi-experimental; diet modification training
R. Huntriss et al., 2018 [74]	HbA1c (%)	Varied (~6.1–9.1%) [74]	At 1 year: LCIA -0.28% vs control [74]	95% CI -0.53 to -0.02, p=0.03; I ² =54% [74]	p=0.03 [74]	Low-carb; medication reductions widespread
Aimee Afable & Nidhi Shree Karingula,	HbA1c; FBG	Varied by study [75]	E.g., pharmacist RCT HbA1c -1.7%, FBG -30.8 mg/dL	Varied by study; range ~-0.6% to -2.2% [75]	Most trials significant [75]	LMICs; 66 interventional studies

Study	Outcome Measure	Baseline (Intervention / Control)	Post-Intervention Effect (Intervention / Control or Change)	Effect Size or Pooled Estimate	p-value / Statistical Significance	Notes
2016 [75]			vs control; nurse follow-up -1.87% at 12 weeks [75]			
Lee-Wen Pai et al., 2016 [76]	HbA1c (SMD)	Not reported [76]	Overall SMD -0.60 [76]	95% CI -0.83 to -0.37; I ² =93% [76]	Significant [76]	Yoga SMD -0.81; Tai chi -0.75; Walking -0.56; Qigong NS
Lal B. Rawal et al., 2021 [77]	HbA1c (SMD)	Varied (e.g., 8.0–10.5%) [77]	Pooled SMD -0.18% [77]	95% CI -0.32 to -0.04, p=0.031; I ² =56.7% [77]	p=0.031 [77]	Migrants/ethnic minorities; peer-led subtotal ~-0.24% [77]
Mihiretu	HbA1c	HbA1c >7.0	Pooled MD	95% CI	Significant	Digital

Study	Outcome Measure	Baseline (Intervention / Control)	Post-Intervention Effect (Intervention / Control or Change)	Effect Size or Pooled Estimate	p-value / Statistical Significance	Notes
M Kebede et al., 2018 [15]	(ANCOVA-adjusted MD)	% required; baseline diff's -0.2% to 0.64% [15]	-0.39% [15]	-0.51 to -0.26; I ² =80.8% [15]	[15]	interventions; 6–8 months most effective (-0.59%) [15]
Ramavtar Sharma et al., 2019 [78]	FBG (mg/dL); PPBS (mg/dL)	B1: FBG 128.8; PPBS 205.0; B2: FBG 163.59; PPBS 244.39 [78]	B1: FBG -18.8, PPBS -38.6 (both p<0.05); B2: FBG -51.7, PPBS -87.1 (p<0.001) [78]	B1 95% CI FBG: 2.9–34.7; B2 95% CI FBG: 48.7–54.8 [78]	B1: FBG p=0.025, PPBS p=0.009; B2: both p<0.001 [78]	Lifestyle+yoga+allopathic meds; Ayurveda adds further benefit
Takahiro Ichikawa et al., 2024	HbA1c (SMD)	Not reported [12]	SMD -0.11 (NS) [12]	95% CI -0.33 to 0.11, p=0.32;	NS (p=0.32) [12]	Long-term (≥12 months) LCD;

Study	Outcome Measure	Baseline (Intervention / Control)	Post-Intervention Effect (Intervention / Control or Change)	Effect Size or Pooled Estimate	p-value / Statistical Significance	Notes
[12]				I ² =41% [12]		triglycerides and HDL improved
Shanshan Chen et al., 2022 [79]	HbA1c (MD); FBG (SMD); PPBG (SMD)	Not reported numerically [79]	HbA1c MD -0.47%; FBG SMD -0.92; PPBG SMD -0.53 [79]	HbA1c: 95% CI -0.77 to -0.16; FBG: 95% CI -1.55 to -0.29; PPBG: 95% CI -0.86 to -0.21 [79]	HbA1c p=0.003; FBG p=0.004; PPBG p=0.001 [79]	Yoga; 13 RCTs; uncomplicated T2DM; high I ² for FBG
Celia Cruz-Cobo & M. J. Santi-Cano, 2020	HbA1c (%)	Range 6–9%; >7% in 84% of studies [80]	Range -1.6% (individual education) to +0.05% (mixed education)	Not pooled [80]	Decrease of 1.6%: p<0.001; increase of 0.05%:	Primary care diabetes education; individual best for

Study	Outcome Measure	Baseline (Intervention / Control)	Post-Intervention Effect (Intervention / Control or Change)	Effect Size or Pooled Estimate	p-value / Statistical Significance	Notes
[80]			[80]		p<0.05 [80]	HbA1c

Discussion of Glycemic Effect Estimates

Across the corpus, lifestyle modifications demonstrate consistent, statistically significant reductions in HbA1c relative to standard or minimal care comparators, though the magnitude of effects varies substantially by intervention type, intensity, population, and duration.

The most rigorously powered evidence comes from large-scale meta-analyses and multi-center RCTs. Comprehensive multicomponent interventions—combining dietary change, structured physical activity, and behavioral/educational support—produce pooled HbA1c reductions of approximately -0.51% to -0.63% [1–3]. The original Look AHEAD trial, the largest primary RCT in the corpus, demonstrated a sustained between-group advantage of approximately -0.27% averaged across four years [20], with the year-one comparison showing that 72.7% of intensive lifestyle intervention participants achieved HbA1c $<7\%$ versus 50.8% in the support-and-education control [32]. Critically, these glycemic gains in Look AHEAD were achieved despite participants in the intensive arm using fewer diabetes medications [20, 32], underscoring the direct pharmacological impact of behavioral change.

Specific lifestyle domains each contribute meaningfully. In the exercise literature, the pooled effect across 16 RCTs of comprehensive lifestyle change yields an HbA1c SMD of -0.37 [30], while exercise-only meta-analyses report significant reductions (e.g., -0.6% for aerobic training alone [56], -0.30% to -0.53% across modalities [7]). The superiority of combined aerobic plus resistance training over either modality alone is a consistent finding across independent meta-

analyses [6–8]. The Church et al. nine-month RCT remains the most methodologically rigorous direct comparison, demonstrating that only combination training achieved a statistically significant HbA1c reduction versus nonexercise control (-0.34% , $p=0.03$), while aerobic (-0.24% , $p=0.14$) and resistance (-0.16% , $p=0.32$) alone did not [8]. A notably consistent moderator across exercise studies is supervision: supervised programs outperform unsupervised programs by approximately 0.53 – 0.60% in HbA1c [7].

Dietary interventions also produce meaningful effects, though the evidence is more nuanced by dietary pattern and time horizon. The DASH diet produced an A1C reduction of -1.7% over eight weeks in a crossover trial [11]. The Mediterranean diet achieved HbA1c reductions of -0.47% [47] to -0.50% [9] in meta-analytic estimates and markedly delayed antihyperglycemic drug initiation (44% vs 70% needing drugs at four years; HR 0.63) [9]. In a network meta-analysis of nine dietary approaches, all patterns reduced HbA1c by -0.47% to -0.82% versus control, with the low-carbohydrate diet ranked best for HbA1c (SUCRA 84%) and the Mediterranean diet ranked best for fasting glucose (SUCRA 88%) [10]. Short-term ketogenic diet interventions showed large within-subject HbA1c reductions of -1.07% and FBG reductions of -1.29 mmol/L [50], though a long-term meta-analysis (≥ 12 months) found no significant between-group HbA1c advantage for low-carbohydrate diets (SMD -0.11 , 95% CI -0.33 to 0.11 , $p=0.32$) [12], likely reflecting adherence attrition over time. Low-carbohydrate diets at shorter durations showed a pooled HbA1c reduction of -0.44% (95% CI -0.61 to -0.26) [40] and a 1-year pooled effect of -0.28% [74], with the caveat that medication reductions in low-carbohydrate arms may blunt the observed glycemic difference [74].

Education-based and self-management interventions are effective particularly over the medium term. Group-based DSME produces pooled HbA1c reductions of -0.44% at six months, -0.46% at twelve months, and -0.87% at two years [13], with single-program data suggesting effects can persist to four to five years [13]. Individual face-to-face education, in contrast, showed no significant overall HbA1c benefit versus usual care (WMD -0.1% , $p=0.33$), with benefit confined to those with baseline HbA1c $>8\%$ (WMD -0.3% , $p=0.007$) [18]. Patient activation interventions broadly (138 RCTs, $n>33,000$) produced a pooled A1c reduction of -0.37% [4], with

pharmacist-led programs, higher baseline HbA1c, and longer intervention duration predicting larger reductions [4].

Digital and technology-assisted delivery modalities have emerged as an important and growing evidence base. Automated brief messaging (SMS) reduces HbA1c by approximately -0.53% [16]. Mobile phone apps yield pooled reductions of -0.49% [17], with healthcare professional feedback a key moderator (-0.56% with versus -0.26% without feedback) [17]. Mobile app-assisted self-care across 27 trials shows HbA1c SMD -0.44 and FBG SMD -0.29 [72]. A cluster-randomized trial of personalized mobile behavioral coaching achieved an exceptionally large 1.2% between-group HbA1c advantage over twelve months [44]. Digital interventions are most effective in those with HbA1c $>7.5\%$ at baseline and during a six-to-eight-month window, after which effects attenuate [15]. Web-based delivery consistently shows significant pooled effects whereas telehealth and SMS alone do not [15].

Yoga represents a distinct and increasingly studied intervention, with meta-analyses consistently showing improvements in HbA1c ($d=0.36$ [62] to MD -0.47% [79]), fasting blood glucose ($d=0.58$; MD -25.56 mg/dL [69]), and postprandial glucose ($d=0.40$) [62]. The leisure-time physical activity meta-analysis found yoga to produce the largest HbA1c reduction among physical activity modalities examined (SMD -0.81 vs -0.56 for walking and -0.04 for qigong) [76].

Two studies with notably high effect sizes deserve contextual interpretation. Girija Kumari et al. (2021) reported an ITT between-group HbA1c difference of -2.82% (95% CI -5.26 to -0.37) [65], and the single-arm cohort of Metwally et al. (2019) showed an absolute HbA1c decline of 2.88 percentage points [64]. Both were conducted in populations with severely elevated baseline HbA1c ($>7\%$ and $>11\%$, respectively) [64, 65], and both used quasi-experimental designs without randomization [64, 65], making inflation from regression to the mean a plausible contributor. Similarly, the Quinn et al. cluster-RCT reported a 1.2% between-group HbA1c difference [44], but enrolled only 163 participants in a primary care setting with high baseline glycemia (~ 9.2 – 9.9%) [44]. These findings are consistent with the robust moderator identified across multiple meta-analyses: higher baseline HbA1c reliably predicts larger absolute treatment effects [1, 4, 15, 18].

Diabetes remission—achieving normoglycemia without medication—is achievable through intensive lifestyle modification. The Look AHEAD ancillary analysis demonstrated remission rates of 11.5% in year one and 7.3% at year four for intensive lifestyle versus approximately 2% in controls [21]. A systematic review of twelve studies across 3,997 patients found an odds ratio of approximately 6.09 (95% CI 3.14 to 11.79) for remission with lifestyle intervention within twelve months [22], driven principally by low-energy dietary programs combined with weight loss of 7 or more kilograms [22].

Secondary Outcomes

Beyond HbA1c and glucose, lifestyle interventions demonstrate broad cardiometabolic benefits. Comprehensive programs consistently reduce body weight, BMI, and blood pressure [20, 30, 32]. The Look AHEAD intensive lifestyle arm achieved an average 6.15% weight loss over four years compared to 0.88% in controls [20], accompanied by HDL increases of 3.67 versus 1.97 mg/dL and triglyceride reductions of −25.56 versus −19.75 mg/dL [20]. Lifestyle interventions also confer fitness improvements, with treadmill fitness increasing by approximately 12.74% in the ILI arm versus 1.96% in DSE across four years [20]. Medication requirements are substantially reduced in high-intensity programs: 95.2% of participants on a low-carbohydrate ketogenic diet reduced or eliminated diabetes medications versus 62.1% on a low-glycemic index diet [25], and look AHEAD participants used fewer glucose-lowering and antihypertensive medications throughout the four-year period despite better glycemic control [20]. Quality of life improvements were reported across DSME-based programs [13, 14, 65], and cognitive function improved alongside glycemic control in one prospective study (conventional therapy was associated with 11.5-fold greater odds of mild cognitive impairment at six months) [53].

Synthesis: Reconciling Heterogeneous Findings

The Core Tension: Why Do Studies Report Such Variable Glycemic Effects?

The pooled estimates across this literature range from −0.11% (non-significant; long-term low-carbohydrate diets [12]) to −2.82% (highly elevated baseline cohort with holistic counseling [65]), a span that cannot be explained by random sampling variation. Three interacting explanatory mechanisms account for most of this heterogeneity.

Baseline Glycemic Status as the Primary Moderator

Across virtually every meta-analysis and subgroup analysis in this corpus, baseline HbA1c is the most consistent predictor of treatment effect magnitude. Studies enrolling participants with HbA1c $\geq 8\%$ report pooled reductions of -0.48% versus -0.28% in those with baseline $< 8\%$ [4]. The same pattern is visible in the individual education literature (benefit confined to HbA1c $> 8\%$ subgroup) [18], in digital interventions (greater benefit when baseline $> 7.5\%$) [15], in exercise trials (subgroup with baseline HbA1c $\geq 7.0\%$ showing combined-training effect of -0.53% vs. -0.34% overall) [8], and in behavioral text-message interventions [61]. This convergence across intervention types and methodologies strongly suggests that the mechanism is shared: individuals with more poorly controlled glycemia have more room for improvement, and lifestyle modifications that influence insulin sensitivity, dietary carbohydrate load, or energy balance will produce proportionally larger absolute glycemic changes in those with higher starting values. Studies reporting small or null effects frequently enrolled participants near glycemic targets or with shorter diabetes duration and lower HbA1c at baseline [70, 74].

Intervention Intensity and Contact Frequency as Dose

The relationship between intervention intensity and glycemic outcomes is demonstrable across multiple intervention types. Within exercise interventions, supervised programs outperform unsupervised ones by $0.53\text{--}0.60\%$ in HbA1c [7], and supervised combined training is the only modality to achieve significance versus nonexercise control in the only major head-to-head four-arm RCT [8]. Within dietary programs, only interventions achieving $\geq 5\%$ weight loss produced significant HbA1c improvements; those producing $< 5\%$ loss did not [23]. Within combined diet-plus-activity programs, HbA1c reductions of -1.11% at three months attenuate to -0.28% at twelve months and -0.26% at twenty-four months [19], directly mapping the waning of contact intensity after the initial active phase. Within DSME, group programs with 19–52 total contact hours produced larger effects than lower-dose programs [13]. Mobile applications with healthcare professional feedback achieve -0.56% versus -0.26% without feedback [17]. This dose-response pattern explains many apparent inconsistencies: studies finding null or trivial effects are

disproportionately those using low-intensity delivery—brief individual education sessions [18], simple physical activity advice [28], or automated text messages alone without feedback loops [15].

The Long-Term Sustainability Problem

A third structural feature of this literature is the consistent attrition of benefit over time, which accounts for apparent discrepancies between short-term and long-term studies. Several mechanisms converge here. First, behavioral adherence to dietary restriction and exercise declines with time; low-carbohydrate diets achieve short-term HbA1c reductions of -0.44% [40] but demonstrate no between-group advantage beyond twelve months as carbohydrate intake drifts toward habitual levels [12]. Second, Look AHEAD—the most intensive intervention in this corpus, with up to 1.5 hours per week of professional contact initially—shows HbA1c advantages that peak at year one and attenuate to approximately -0.27% averaged over four years [20]. Third, glycemic improvement itself may reduce the magnitude of possible subsequent improvement (regression toward the mean in ongoing participants). Programs that maintain sustained contact—monthly group DSME over years [13], continuous app-based monitoring [15], or ongoing counseling with refresher campaigns [21]—show more durable effects. The critical insight from the combined exercise literature is instructive: the addition of structured exercise to diet produced only infrequent additional glycemic improvements beyond diet alone in short-duration RCTs [37], yet the longer-running combined lifestyle programs consistently outperform their components. The time-scale at which interventions are evaluated thus substantially determines whether a "positive" or "null" result is observed for any given lifestyle component.

The Weight Loss Mediation Question

Several sources treat weight loss as the primary mediator of glycemic improvement from lifestyle modification [1, 10, 23]. The evidence both supports and complicates this framing. The Franz et al. meta-analysis found that a 5% or greater weight loss threshold was necessary for significant HbA1c improvement in lifestyle weight-loss trials [23]. García-Molina et al. document that greater weight loss differences between intervention and control were associated with larger HbA1c reductions [1]. However, the Toledo et al. mechanistic study found that exercise energy expenditure predicted insulin sensitivity improvements ($r=0.84$), and that skeletal muscle

mitochondrial content restoration was a strong correlate of HbA1c reduction, independent of the degree of weight loss [24]. Church et al. found significant HbA1c benefit from combined training in those starting with HbA1c $\geq 7.0\%$ without clinically meaningful weight loss differences between exercise groups [8]. Similarly, the low-carbohydrate diet trials show significant HbA1c reductions—and particularly marked medication reductions—that persist after statistical adjustment for weight loss [9, 25]. These findings suggest that while weight loss is an important mediator, particularly for obese individuals, it is not the only pathway; glycemic benefit can arise directly from increased skeletal muscle glucose uptake through exercise, from reduced postprandial carbohydrate load, and from improved insulin sensitivity in the liver and peripheral tissues, all of which are modifiable by lifestyle change independent of large weight reductions.

What Can Be Concluded for Specific Contexts

For adults with T2DM and HbA1c $\geq 8\%$: The evidence strongly supports multicomponent intensive lifestyle interventions—combining dietary modification, supervised combined exercise, and behavioral support with frequent contact—as producing clinically meaningful HbA1c reductions of 0.5–1.0% or greater. Both pharmacist-led individualized DSME [52] and nurse-led hospital-based programs [5] achieve similarly large effects in this population. Digital interventions with real-time provider feedback [17, 44] and web-based platforms [15] are viable as adjuncts or where in-person delivery is not feasible.

For adults with T2DM and HbA1c $< 8\%$: Reductions are smaller, and some intervention types (individual education overall, resistance training alone, general physical activity advice) may not achieve statistical significance in well-powered studies [8, 18, 28]. In this glycemic range, the primary benefit of ongoing lifestyle modification may be maintenance of control, prevention of progression, and reduction of medication requirements rather than large absolute HbA1c reductions.

For newly diagnosed T2DM: Mediterranean dietary patterns [9] and intensive lifestyle programs [21] show particularly favorable responses, likely because the pathophysiological cascade of beta-cell exhaustion and secondary complications is less advanced. Remission—defined as achieving normoglycemia without medication—is plausible in 7–12% of participants over one to

four years of intensive intervention [21, 22], and dietary approaches (especially low-energy or low-carbohydrate patterns) are central to remission protocols [22].

For specific dietary patterns: At twelve months, all studied dietary approaches improve HbA1c relative to minimal care [10], but no single pattern demonstrates consistent superiority over others beyond twelve months after accounting for adherence [12]. The Mediterranean diet has the most robust long-term evidence base and simultaneously addresses lipid profile, blood pressure, and cardiovascular risk [9, 47]. Low-carbohydrate approaches show the most pronounced medication-reduction effects and are particularly effective in the short term for motivated patients, but require closer medical monitoring due to hypoglycemia risk from concurrent diabetes medications [25, 74].

For low- and middle-income countries: Lifestyle interventions demonstrate pooled HbA1c reductions of -0.63% [2] similar to high-income settings. Healthcare professional-led, hospital-based, multi-topic DSME programs are most effective; peer-led and home-based programs show smaller, less consistent effects [2]. Culturally adapted programs using community health workers and peer educators produce modest but statistically significant improvements (pooled -0.18%) [77], and represent the most scalable approach in resource-limited settings.

For special populations: Adults with T2DM and comorbid schizophrenia benefit from behaviorally adapted DSME that accommodates cognitive deficits through simplified, gradual instruction and environmental resource provision, though HbA1c effects may require longer intervention durations to become measurable [71]. Migrants and ethnic minorities show consistent benefit from culturally and linguistically tailored peer-support programs [77].

DISCUSSION

The results of this systematic review demonstrate that lifestyle modifications consistently improve glycemic control in adults with T2DM, but the magnitude of benefit varies substantially across studies, from non-significant effects (e.g., long-term low-carbohydrate diets, individual face-to-face education in well-controlled patients) to clinically dramatic reductions exceeding 2% HbA1c (e.g., intensive holistic counseling in poorly controlled populations). Rather than treating these discrepancies as contradictions, our synthesis identifies three interacting explanatory

mechanisms—baseline glycemic status, intervention intensity, and sustainability—that systematically account for the observed heterogeneity (Wing, 2010; Gregg et al., 2012).

Baseline Glycemic Status as the Primary Moderator

The most consistent and powerful moderator across all intervention types is baseline HbA1c. Studies enrolling participants with HbA1c $\geq 8\%$ report pooled reductions twice as large as those with baseline $< 8\%$ (Bolen et al., 2014). This pattern appears repeatedly: in digital interventions, greater benefit is observed when baseline HbA1c exceeds 7.5% (Kebede et al., 2018); in individual diabetes education, the only subgroup showing significant improvement is those with baseline $> 8\%$ (Duke et al., 2009); in the Church et al. exercise trial, combined training produced significant HbA1c reduction only in participants starting with HbA1c $\geq 7.0\%$ (Church et al., 2010); and in text-message interventions, baseline glycemia predicts response (Şahin et al., 2019).

This phenomenon reflects a combination of statistical and biological mechanisms. Statistically, regression to the mean inflates observed improvements in high-baseline groups. Biologically, individuals with poorer control have more reversible pathology: higher levels of glucotoxicity, greater room for improvement in insulin sensitivity, and more substantial benefit from reducing dietary carbohydrate load or increasing physical activity (Mitra et al., 2012). The clinical implication is that lifestyle interventions should be targeted preferentially to patients with suboptimal control (HbA1c $\geq 7.5\text{--}8.0\%$), where the expected absolute benefit is largest (Zhang et al., 2022).

Intervention Intensity and Dose-Response Relationship

A clear dose-response relationship exists between intervention intensity and glycemic outcome. Within exercise trials, supervised programs outperform unsupervised programs by 0.53–0.60% in HbA1c reduction (Pan et al., 2018). The only head-to-head four-arm RCT comparing aerobic, resistance, combined, and control conditions demonstrated that only combined supervised training achieved significant HbA1c reduction versus control (-0.34% , $p=0.03$), while aerobic (-0.24%) and resistance (-0.16%) alone did not (Church et al., 2010). Similarly, in dietary trials, only interventions achieving $\geq 5\%$ weight loss produced significant HbA1c improvements; those with $< 5\%$ loss showed no benefit (Franz et al., 2015). Within DSME, group programs with

19–52 total contact hours produced larger effect sizes than lower-dose programs (Steinsbekk et al., 2012). Mobile health applications with healthcare professional feedback achieve -0.56% HbA1c reduction, whereas those without feedback achieve only -0.26% (Hou et al., 2016). The Italian Diabetes and Exercise Study (IDES), which employed intensive supervised exercise with counseling, demonstrated significant improvements in HbA1c, 2-hour glucose, and glucose iAUC compared to counseling alone (Balducci et al., 2010).

This dose-response relationship explains why low-intensity interventions—brief individual education sessions (Duke et al., 2009), unstructured physical activity advice (Sanghani et al., 2013), or automated text messages without feedback (Arambepola et al., 2016)—frequently yield null or trivial effects. It also supports the use of health coaching, which by definition involves ongoing personalized contact, as an effective delivery modality (Sulfikar et al., 2023).

The Long-Term Sustainability Problem

A third structural feature of the evidence base is the consistent attenuation of glycemic benefit over time, which explains the discrepancy between short-term (≤ 6 months) and long-term (≥ 12 months) studies. Four mechanisms contribute to this attenuation. First, behavioral adherence to dietary restriction and structured exercise inevitably declines after the active intervention phase (Cradock et al., 2017). Second, the Look AHEAD trial, the most intensive intervention in the corpus (up to 1.5 hours/week of professional contact initially), showed peak HbA1c advantage at year 1, which attenuated to an average of -0.27% over four years (Wing, 2010). Third, low-carbohydrate diets achieve short-term HbA1c reductions of -0.44% (Meng et al., 2017) but demonstrate no between-group advantage beyond 12 months as carbohydrate intake drifts toward habitual levels (Ichikawa et al., 2024). Fourth, the combination of diet and exercise, while producing -1.11% HbA1c reduction at 3 months, attenuates to -0.28% at 12 months and -0.26% at 24 months (Cradock et al., 2017).

Programs that maintain sustained contact—monthly group DSME over years (Steinsbekk et al., 2012), continuous app-based monitoring with feedback (Kebede et al., 2018), or ongoing counseling with refresher campaigns (Gregg et al., 2012)—show more durable effects. This suggests that lifestyle modification for T2DM should be conceptualized as a chronic care

intervention requiring ongoing support, not a time-limited educational course (Odgers-Jewell et al., 2017).

The Role of Weight Loss as a Mediator

The relationship between weight loss and glycemic improvement is both supported and nuanced. Meta-analyses confirm that achieving $\geq 5\%$ weight loss is necessary for significant HbA1c reduction in lifestyle weight-loss trials (Franz et al., 2015), and greater weight loss differences between intervention and control groups correlate with larger HbA1c reductions (García-Molina et al., 2019). However, weight loss is not the sole mediator. The Toledo et al. mechanistic study found that exercise energy expenditure predicted improvement in insulin sensitivity ($r=0.84$), and that restoration of skeletal muscle mitochondrial content was a strong correlate of HbA1c reduction, independent of weight loss (Toledo et al., 2007). Church et al. found significant HbA1c benefit from combined training without clinically meaningful weight loss differences between exercise groups (Church et al., 2010). Low-carbohydrate diet trials show medication reductions and HbA1c improvements that persist after statistical adjustment for weight loss (Westman et al., 2008). The Mediterranean diet delays antihyperglycemic drug initiation (HR 0.63) without requiring large weight loss (Esposito et al., 2009).

These findings indicate that glycemic benefit can arise through multiple independent pathways: (1) weight loss-mediated improvement in hepatic and peripheral insulin sensitivity (Franz et al., 2015); (2) increased skeletal muscle glucose uptake from regular exercise, independent of weight (Pan et al., 2018); (3) reduced postprandial carbohydrate load from low-carbohydrate or low-glycemic index diets (Meng et al., 2017); (4) improved mitochondrial oxidative capacity (Toledo et al., 2007); and (5) enhanced dietary quality (e.g., Mediterranean pattern) that improves insulin sensitivity through anti-inflammatory mechanisms (Esposito et al., 2015). The practical implication is that lifestyle interventions should not be judged solely by weight loss; even without substantial weight reduction, meaningful glycemic benefits can accrue (Terranova et al., 2015).

Specific Intervention Domains

Exercise interventions show consistent efficacy across multiple meta-analyses. Aerobic training reduces HbA1c by approximately -0.6% , combined training by -0.67% , while resistance

training alone shows inconsistent effects (Chudyk & Petrella, 2011; Thomas et al., 2006). A network meta-analysis confirmed that combined aerobic and resistance training is superior to either modality alone, with combined training ranked best for HbA1c reduction (Schwingshackl et al., 2014). The effectiveness of exercise is further supported by 40 studies showing that aerobic exercise—including walking and aerobic gymnastics—significantly reduces blood glucose (Bariyyah et al., 2021). Importantly, the glycemic benefit of exercise occurs even in the absence of weight loss, mediated by increased GLUT-4 translocation and improved capillary density in skeletal muscle (Mitra et al., 2012).

Dietary interventions demonstrate that multiple patterns are effective, but with different time horizons and metabolic effects. The DASH diet produced an impressive -1.7% HbA1c reduction over eight weeks in a crossover trial (Azadbakht et al., 2010). The Mediterranean diet achieves HbA1c reductions of -0.47% to -0.50% in meta-analyses and, importantly, reduced the need for antihyperglycemic drug initiation (44% vs. 70% needing drugs at 4 years; HR 0.63) (Esposito et al., 2009; Esposito et al., 2015). A network meta-analysis of nine dietary approaches found that all patterns reduced HbA1c by -0.47% to -0.82% versus control, with low-carbohydrate ranked best for HbA1c and Mediterranean ranked best for fasting glucose (Schwingshackl et al., 2018). Short-term ketogenic diets produce large within-subject HbA1c reductions (-1.07%) and FBG reductions (-1.29 mmol/L), but long-term (≥ 12 months) meta-analyses show no between-group advantage (Yuan et al., 2020; Ichikawa et al., 2024). Low-carbohydrate diets at one year produce a pooled HbA1c reduction of -0.28% (95% CI -0.53 to -0.02), but medication reductions in the low-carbohydrate arm may blunt the observed glycemic difference (Huntriss et al., 2018). Vegetarian diets reduce HbA1c by -0.39% (Yokoyama et al., 2014). The gut microbiota is increasingly recognized as a mediator of dietary effects, with high-fiber, Mediterranean, and low-carbohydrate diets all producing favorable shifts in microbial composition that correlate with improved glycemia (Farahbod et al., 2024).

Diabetes self-management education (DSME) is highly effective, particularly when delivered in group formats. Group-based DSME reduces HbA1c by -0.44% at 6 months, -0.46% at 12 months, and -0.87% at 2 years (Steinsbekk et al., 2012). A large meta-analysis of 28 RCTs

(8,533 participants) found a pooled MD of -0.34% (95% CI -0.51 to -0.17) at primary time points, with effects sustained to 36–48 months (MD -0.93%) (Odgers-Jewell et al., 2017). In contrast, individual face-to-face education showed no significant overall HbA1c benefit (WMD -0.1% , $p=0.33$), with benefit confined to those with baseline HbA1c $>8\%$ (WMD -0.3% , $p=0.007$) (Duke et al., 2009). Patient activation interventions broadly (138 RCTs, $n>33,000$) produced a pooled HbA1c reduction of -0.37% (Bolen et al., 2014). Pharmacist-led interventions and DSME in Middle Eastern countries show particular effectiveness, with absolute HbA1c reductions of -1.05% , FBG reductions of -27 mg/dL, and non-fasting BG reductions of -44 mg/dL (Mikhael et al., 2020; Pousinho et al., 2016).

Digital and mobile health (mHealth) interventions have emerged as scalable alternatives. Automated brief messaging (SMS) reduces HbA1c by approximately -0.53% (Arambepola et al., 2016). Mobile phone apps yield pooled reductions of -0.49% , with healthcare professional feedback as a critical moderator (-0.56% with feedback vs. -0.26% without) (Hou et al., 2016). Smartphone app-assisted self-care across 27 trials shows HbA1c SMD -0.44 and FBG SMD -0.29 (Cui et al., 2016; Liu et al., 2019). A cluster-randomized trial of personalized mobile behavioral coaching achieved an exceptionally large 1.2% between-group HbA1c advantage over 12 months (Quinn et al., 2011). Digital interventions are most effective in those with HbA1c $>7.5\%$ at baseline and during a 6- to 8-month window, after which effects attenuate (Kebede et al., 2018). Web-based delivery consistently shows significant pooled effects, whereas telehealth and SMS alone do not (Cotter et al., 2014). mHealth interventions also improve medication adherence (Andriyana et al., 2023). Tailored mobile text messaging produces a Hedges' g of 0.54 (95% CI 0.08 – 0.99) for HbA1c reduction (Şahin et al., 2019).

Yoga represents a distinct and increasingly studied mind-body intervention. Meta-analyses consistently show improvements in HbA1c ($d+=0.36$ to MD -0.47%), fasting blood glucose ($d+=0.58$ to MD -25.56 mg/dL), and postprandial glucose ($d+=0.40$) (Thind et al., 2017; Innes & Selfe, 2015; Chen et al., 2022). The leisure-time physical activity meta-analysis found yoga to produce the largest HbA1c reduction among all physical activity modalities (SMD -0.81), compared to walking (SMD -0.56) and qigong (SMD -0.04) (Pai et al., 2016). Yoga interventions

are typically delivered in group settings and combine physical postures, breathing exercises, and meditation, suggesting that stress reduction and autonomic nervous system modulation may contribute to glycemic benefits beyond physical activity alone (Sharma et al., 2019). For uncomplicated T2DM, yoga significantly improves HbA1c (MD -0.47% , 95% CI -0.77 to -0.16), FBG (SMD -0.92), and PPBG (SMD -0.53) (Chen et al., 2022).

Diabetes Remission as a Distinct Outcome

A paradigm-shifting finding from the literature is that intensive lifestyle modification can achieve diabetes remission—defined as achieving normoglycemia without active glucose-lowering medication. In the Look AHEAD ancillary analysis, remission rates were 11.5% at year 1 and 7.3% at year 4 in the intensive lifestyle arm versus approximately 2% in controls (Gregg et al., 2012). A systematic review of 12 studies (3,997 patients) found an odds ratio of approximately 6.09 (95% CI 3.14–11.79) for remission with lifestyle intervention within 12 months (Zhang et al., 2022). Remission is most achievable in patients with shorter diabetes duration, lower baseline HbA1c, and greater weight loss (≥ 7 kg), and is driven principally by low-energy dietary programs combined with substantial weight reduction (Zhang et al., 2022). The concept of remission changes the clinical goal from "control" to "disease modification," although sustained remission beyond 5 years remains challenging (Gregg et al., 2012).

Secondary Outcomes

Beyond glycemic control, lifestyle interventions produce broad cardiometabolic benefits. The Look AHEAD intensive lifestyle arm achieved average weight loss of 6.15% over 4 years versus 0.88% in controls, accompanied by HDL increases of 3.67 vs. 1.97 mg/dL and triglyceride reductions of -25.56 vs. -19.75 mg/dL (Wing, 2010). Fitness improvements are substantial, with treadmill fitness increasing by approximately 12.74% in the ILI arm versus 1.96% in DSE over 4 years (Wing, 2010). Medication requirements are substantially reduced: 95.2% of participants on a low-carbohydrate ketogenic diet reduced or eliminated diabetes medications versus 62.1% on a low-glycemic index diet (Westman et al., 2008). In Look AHEAD, ILI participants used fewer glucose-lowering and antihypertensive medications throughout the 4-year period despite better glycemic control (Pi-Sunyer et al., 2007). Quality of life improvements are reported across DSME-

based programs (Steinsbekk et al., 2012; Odgers-Jewell et al., 2017; Kumari et al., 2021). Cognitive function also improves alongside glycemic control: one prospective study found that conventional therapy was associated with 11.5-fold greater odds of mild cognitive impairment at 6 months compared to lifestyle modification (Salama et al., 2023). Blood pressure reductions are consistently observed (Azadbakht et al., 2010; Esposito et al., 2015).

Specific Populations

Low- and middle-income countries (LMICs): Lifestyle interventions demonstrate pooled HbA1c reductions of -0.63% (95% CI -0.86 to -0.40) and FBG SMD of -0.35 (95% CI -0.54 to -0.16) in LMICs, comparable to high-income settings (O'Donoghue et al., 2021). Healthcare professional-led, hospital-based, multi-topic DSME programs are most effective; peer-led and home-based programs show smaller, less consistent effects (O'Donoghue et al., 2021). A broader evidence review of 66 studies in LMICs found effect sizes ranging from approximately -0.6% to -2.2% HbA1c reduction, with pharmacist-led RCTs showing -1.7% HbA1c and -30.8 mg/dL FBG (Afable & Karingula, 2016). In rural Egypt, a health education program counteracting lifestyle barriers produced an absolute HbA1c decline of 2.88 percentage points (Metwally et al., 2019). In rural China, real-life lifestyle interventions (meal order, physical activity, breathing exercises) significantly reduced FBG and HbA1c in a quasi-experimental design (Wang et al., 2020). In Pakistan, a 12-week lifestyle medicine RCT showed significant improvements in HbA1c, FBG, and PPG compared to standard medical care (Sabir et al., 2025). The NPCDCS-AYUSH integration project in India found that Ayurveda plus yoga plus lifestyle modification added further benefit beyond lifestyle plus allopathy (Sharma et al., 2019).

Migrants and ethnic minorities: Culturally and linguistically tailored lifestyle interventions among migrants and ethnic minorities living in industrialized countries produce modest but statistically significant pooled HbA1c reductions (SMD -0.18% , 95% CI -0.32 to -0.04) (Rawal et al., 2021). Peer-led programs (subtotal SMD approximately -0.24%) appear more effective than professional-led programs in these populations, likely due to improved cultural resonance (Rawal et al., 2021).

Comorbid schizophrenia: Adults with T2DM and comorbid schizophrenia benefit from behaviorally adapted DSME that accommodates cognitive deficits through simplified, gradual instruction and environmental resource provision (Cimo et al., 2012). However, HbA1c effects may require longer intervention durations to become measurable; one study showed significant FBG reduction (-17.8 mg/dL, $p<0.001$) but non-significant HbA1c changes at 6 or 12 months (Cimo et al., 2012).

Family-supported interventions: Family support integrated with DSME enhances glycemic control, with 10 out of 23 studies showing up to approximately 1% HbA1c reduction (Pamungkas et al., 2017). Social support more broadly is associated with improved HbA1c, though the evidence is largely qualitative (Strom & Egede, 2012).

Comparison with Pharmacological Interventions

One meta-analysis directly compared lifestyle plus pharmacological interventions versus standard care, finding that lifestyle plus pharmacotherapy reduces HbA1c by MD -0.61% (95% CI -0.79 to -0.43) compared to standard care, with lifestyle alone (added to pharmacotherapy) providing a further -0.32% reduction (Abrar et al., 2025). This suggests that lifestyle modifications and medications have additive effects. Importantly, lifestyle interventions achieve these glycemic benefits while reducing medication requirements, which is clinically meaningful for patients experiencing side effects or wishing to minimize polypharmacy (Westman et al., 2008; Pi-Sunyer et al., 2007).

Mechanisms

The mechanistic literature, though limited, provides biological grounding for the observed effects. Exercise increases skeletal muscle mitochondrial content, and the change in mitochondrial density correlates strongly with improved glucose control ($r=0.68-0.84$) (Toledo et al., 2007). Dietary interventions, particularly low-carbohydrate and Mediterranean patterns, reduce postprandial glucose excursions and improve hepatic insulin sensitivity (Mitra et al., 2012). The gut microbiota mediates some dietary effects, with fiber fermentation producing short-chain fatty acids that improve insulin sensitivity (Farahbod et al., 2024). Continuous glucose monitoring (CGM)-assisted lifestyle programs (Glycemic Excursion Minimization, GEM) produce significant HbA1c

reductions (−1.1% between-group difference) and medication reductions, suggesting that real-time feedback on glucose excursions enhances behavioral change (Cox et al., 2020).

Clinical and Research Implications

For clinical practice, the evidence supports several actionable recommendations. For patients with HbA1c $\geq 8.0\%$, intensive multicomponent lifestyle interventions—combining dietary modification, supervised combined exercise (aerobic + resistance), and group-based DSME with ongoing support—should be prescribed as adjuncts to pharmacotherapy. For patients with HbA1c $< 7.5\%$, lifestyle interventions may be framed primarily for maintenance of control, medication reduction, and cardiovascular risk reduction rather than large absolute HbA1c improvements. For newly diagnosed patients, Mediterranean dietary patterns and intensive lifestyle programs offer the best chance of remission, and clinicians should discuss remission as a potential goal. Digital interventions with provider feedback are reasonable alternatives when in-person programs are inaccessible, particularly for patients with baseline HbA1c $> 7.5\%$.

For future research, priorities include: (1) head-to-head RCTs comparing different lifestyle components with standardized outcome measures; (2) longer-duration trials (≥ 24 months) with active maintenance phases to test sustainability strategies; (3) mechanistic studies that identify baseline predictors of response to enable precision lifestyle medicine; (4) pragmatic effectiveness trials in real-world, multimorbid, and diverse populations; (5) cost-effectiveness analyses to inform reimbursement and policy; (6) studies on safety and adverse event monitoring; (7) trials of lifestyle interventions as first-line therapy before pharmacotherapy in newly diagnosed T2DM; and (8) research on behavioral maintenance techniques (e.g., gamification, financial incentives, peer support) to prevent the typical attenuation of benefit beyond 12 months.

CONCLUSION AND RECOMMENDATIONS

Conclusion

This systematic review demonstrates that lifestyle modifications—including dietary changes, structured exercise, diabetes self-management education, digital tools, and yoga—significantly improve blood sugar control in adults with Type 2 Diabetes Mellitus. The pooled

HbA1c reduction of 0.5–0.6% for multicomponent interventions is clinically meaningful and comparable to the effect of adding a second-line oral agent. However, the magnitude of benefit is highly context-dependent: patients with higher baseline HbA1c ($\geq 8\%$) experience twice the absolute reduction compared to those near target; intensive, supervised, and multicomponent programs outperform low-intensity or single-domain interventions; and glycemic benefits attenuate over time without ongoing contact. Weight loss is an important but not exclusive mediator; direct effects on skeletal muscle glucose uptake, postprandial carbohydrate handling, and insulin sensitivity contribute independently. Diabetes remission (normoglycemia without medication) is achievable in 7–12% of participants undergoing intensive lifestyle change, particularly when substantial weight loss (≥ 7 kg) occurs. Secondary benefits—weight loss, blood pressure reduction, improved lipid profiles, decreased medication requirements, and enhanced quality of life—support lifestyle modification as a cornerstone of comprehensive T2DM management across global settings.

Recommendations

For clinical practice:

1. Prescribe multicomponent lifestyle interventions (diet + structured exercise + DSME) as standard adjunctive therapy for T2DM, especially for patients with HbA1c $\geq 8.0\%$.
2. Supervised combined aerobic and resistance training (at least 2–3 sessions/week) should be recommended over aerobic or resistance training alone.
3. Group-based DSME with ongoing monthly contact is preferred over individual education, except for patients with very high baseline HbA1c ($>8\%$) where individual education also provides benefit.
4. Mediterranean and DASH dietary patterns have the strongest long-term evidence; low-carbohydrate diets are effective short-term but require medication adjustment and careful monitoring.

5. Digital interventions (mobile apps, SMS) with healthcare professional feedback are effective when in-person programs are inaccessible; automated or unidirectional digital tools without feedback are not recommended as standalone interventions.
6. For patients interested in mind-body approaches, yoga is a viable option with documented glycemic benefits.
7. Discuss diabetes remission as a potential goal for motivated, newly diagnosed, or recently diagnosed patients with overweight/obesity.

For policy and public health:

1. Invest in community-based, culturally adapted lifestyle programs in low- and middle-income countries, where effect sizes are comparable to high-income settings.
2. Develop peer-supported and family-supported DSME programs for migrants, ethnic minorities, and populations with low health literacy.
3. Reimburse lifestyle interventions as medical treatments, not merely as prevention programs, recognizing their glycemic efficacy comparable to pharmacological add-ons.
4. Integrate DSMES into routine primary care and diabetes clinic workflows, with dedicated non-physician educators (nurses, pharmacists, dietitians, exercise physiologists).

For future research:

1. Conduct long-duration (≥ 24 months) RCTs with active maintenance phases to identify strategies that sustain glycemic improvement beyond 12 months.
2. Perform pragmatic effectiveness trials in real-world, diverse, multimorbid populations to complement explanatory efficacy trials.
3. Develop and validate prediction models that identify which patients are most likely to respond to specific lifestyle components (precision lifestyle medicine).

4. Include formal cost-effectiveness analyses and adverse event monitoring in trial designs.
5. Test lifestyle interventions as first-line therapy in newly diagnosed T2DM compared to initial pharmacotherapy.
6. Standardize outcome definitions (e.g., timing of HbA1c assessment, remission criteria) and intervention reporting (e.g., using the TIDieR checklist) to facilitate meta-analyses.

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