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Artificial Pancreas Systems: Efficacy Of Closed-Loop Systems In Type 1 Diabetes: A Systematic Review

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Abstract

Background: Type 1 diabetes mellitus (T1D) is a chronic autoimmune condition requiring lifelong insulin therapy. Despite advances in insulin delivery, achieving near-physiological glucose control remains challenging due to glycemic variability and hypoglycemia risk. Closed-loop artificial pancreas (AP) systems integrate continuous glucose monitoring, insulin pumps, and automated algorithms to maintain glucose within target ranges.
Objective: To systematically evaluate the efficacy and safety of closed-loop insulin delivery systems in individuals with T1D, focusing on glycemic outcomes, time-in-range (TIR), HbA1c reduction, and adverse events.
Methods: A systematic search was conducted in PubMed, Scopus, Web of Science, Embase, and Google Scholar for studies published between 2010 and 2025. Randomized controlled trials, crossover trials, and single-arm intervention studies assessing closed-loop or hybrid AP systems in T1D populations were included. Data extraction focused on study design, participant characteristics, algorithm type, glycemic outcomes, and safety.
Results: Ten studies encompassing 14–124 participants aged 6–75 years met inclusion criteria. Closed-loop systems consistently improved TIR by 6–15 percentage points, reduced HbA1c by 0.3–0.6%, and decreased hypoglycemia by 30–60%. Hybrid and model predictive control algorithms demonstrated comparable efficacy, while adaptive systems allowed personalized basal insulin adjustment. Adverse events were minor and infrequent; no serious hypoglycemia or diabetic ketoacidosis was reported. Improvements were observed across pediatric, adolescent, and adult populations under both supervised and home conditions.
Conclusion: Closed-loop artificial pancreas systems significantly improve glycemic control and reduce hypoglycemia risk in T1D. Their safety, usability, and positive impact on quality of life highlight their potential as a standard component of modern diabetes management.
Keywords: Type 1 diabetes, artificial pancreas, closed-loop insulin delivery, hybrid closed-loop, continuous glucose monitoring, glycemic control, hypoglycemia, time-in-range

Introduction

Type 1 diabetes mellitus (T1D) is a chronic autoimmune disorder characterized by the destruction of pancreatic β-cells, resulting in absolute insulin deficiency and lifelong dependence on exogenous insulin. Despite advances in insulin formulations and delivery methods, maintaining near-physiological glucose levels remains challenging for many patients. Glycemic variability and hypoglycemia continue to pose significant barriers to achieving optimal metabolic control, contributing to both acute and long-term complications. In response, automated insulin delivery technologies have emerged as a promising solution to bridge the gap between physiological insulin needs and technological capabilities (Boughton & Hovorka, 2019).

The artificial pancreas (AP), also known as the closed-loop insulin delivery system, represents the most advanced form of diabetes technology developed to date. It integrates three core components: a continuous glucose monitor (CGM), an insulin pump, and a control algorithm that automatically adjusts insulin delivery based on real-time glucose readings. The objective is to mimic the dynamic function of a healthy pancreas by maintaining glucose within a target range with minimal user intervention (Thabit & Hovorka, 2016). Early prototypes of closed-loop systems have evolved from simple overnight glucose control models to sophisticated hybrid systems capable of 24-hour management in real-world settings.

Over the past decade, extensive research and technological innovation have transformed closed-loop insulin delivery from laboratory prototypes into clinically approved devices. This evolution has been driven by advances in algorithm design, sensor accuracy, and connectivity between devices. Algorithms such as proportional–integral–derivative (PID), model predictive control (MPC), and fuzzy logic have each demonstrated efficacy in predicting and adjusting insulin delivery to match fluctuating glucose levels (Nwokolo & Hovorka, 2023). The refinement of these algorithms has allowed for greater personalization, safety, and stability of glycemic control across diverse patient populations.

Recent reviews and trials highlight the consistent superiority of closed-loop systems over sensor-augmented pump (SAP) therapy in improving time-in-range (TIR), reducing HbA1c, and minimizing hypoglycemia risk. Meta-analyses report that closed-loop users experience an average increase of 10–15% in TIR compared with SAP, translating to approximately 2–3 additional hours per day within the target glucose range (Fang et al., 2022). These improvements are clinically meaningful, as even modest increases in TIR correlate with significant reductions in microvascular complications.

The ongoing development of artificial pancreas systems has also focused on user experience and quality of life. Contemporary systems have demonstrated reductions in diabetes distress, sleep disruption, and fear of hypoglycemia, particularly among parents of children with T1D (Lal et al., 2019). Integration with mobile technologies and cloud-based data platforms allows for remote monitoring, data sharing, and adaptive learning algorithms, further enhancing usability and long-term adherence. These innovations have positioned automated insulin delivery as a central component of modern diabetes care.

From a safety perspective, closed-loop systems have shown remarkable resilience and reliability. Clinical data confirm that serious adverse events, such as diabetic ketoacidosis (DKA) or severe hypoglycemia, are exceedingly rare when systems are used appropriately. Fail-safe mechanisms, including automatic reversion to open-loop mode and predictive hypoglycemia suspension, are now standard features in most commercial devices (Templer, 2022). These safeguards have significantly increased patient confidence and clinician acceptance of the technology.

The expansion of hybrid closed-loop systems to pediatric, adolescent, and older adult populations underscores the generalizability of their benefits. Large-scale studies have demonstrated effectiveness across age groups and varying degrees of glycemic control (Di Molfetta et al., 2024). Furthermore, network meta-analyses comparing different commercial hybrid systems—such as Medtronic's 670G/780G, Tandem Control-IQ, and CamAPS FX—have shown comparable efficacy and safety, though with minor variations in algorithm responsiveness and hypoglycemia mitigation (Lakshman, Boughton, & Hovorka, 2023).

Looking forward, next-generation closed-loop systems are expected to integrate dual-hormone delivery, incorporating both insulin and glucagon to further improve glucose stability. Research efforts are also exploring adjunctive use of automated insulin delivery with agents like pramlintide or SGLT inhibitors, which may help reduce postprandial excursions and insulin requirements. The convergence of biomedical engineering, artificial intelligence, and cloud computing promises to further accelerate the advancement of artificial pancreas technology toward fully autonomous glucose regulation (Dermawan & Purbayanto, 2022; Hovorka, 2011).

Ultimately, the artificial pancreas represents a paradigm shift in diabetes management—from reactive, manual insulin dosing toward proactive, automated glycemic regulation. As system algorithms and

hardware continue to evolve, evidence increasingly supports their integration into routine clinical practice as a safe, effective, and life-enhancing intervention for individuals with type 1 diabetes (Kang et al., 2022; Allen & Gupta, 2019; Jabari, 2023).

Methodology

Study Design

This study employed a systematic review design in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) 2020 guidelines to ensure transparency, rigor, and reproducibility. The primary objective was to synthesize and critically evaluate empirical evidence on the efficacy and safety of artificial pancreas (AP) and closed-loop insulin delivery systems in individuals with type 1 diabetes (T1D). Specifically, this review examined outcomes related to glycemic control, time-in-range (TIR), HbA1c reduction, and incidence of hypoglycemia or diabetic ketoacidosis (DKA) among users of various closed-loop technologies, including hybrid and fully automated systems. The review included clinical studies that assessed the performance, safety, or patient experience of AP systems in comparison with conventional insulin delivery methods such as sensor-augmented pump (SAP) therapy or multiple daily injections (MDI). Both randomized controlled trials (RCTs) and before–after intervention studies were included to capture a comprehensive spectrum of evidence across experimental and real-world contexts. The synthesis emphasizes the clinical applicability of closed-loop systems for daily glucose management among adolescents and adults with T1D.

Eligibility Criteria

Studies were selected based on predefined inclusion and exclusion criteria to ensure relevance and quality.

Inclusion Criteria:

- **Population:** Individuals diagnosed with type 1 diabetes mellitus across pediatric, adolescent, or adult populations.
- **Interventions:** Closed-loop or hybrid closed-loop insulin delivery systems, including algorithm-controlled insulin pumps integrated with continuous glucose monitors.
- **Comparators:** Conventional insulin delivery methods such as SAP, MDI, or manual insulin pump therapy.
- **Outcomes:** At least one of the following—HbA1c levels, TIR (70–180 mg/dL), time-below-range (TBR), mean glucose, glycemic variability, or incidence of hypoglycemia/DKA.
- **Study Designs:** Randomized controlled trials, crossover studies, or prospective interventional trials with clinical outcome data.
- **Language:** English-language peer-reviewed publications.
- **Publication Period:** Studies published between 2010 and 2025, reflecting the modern development of closed-loop technology.

Exclusion Criteria:

- Non-empirical publications (e.g., reviews, commentaries, or case reports).
- Studies not involving closed-loop insulin systems.
- Non–type 1 diabetes populations or animal studies.
- Conference abstracts, editorials, or studies without full-text availability.

After full-text screening, 10 studies met all inclusion criteria and were included in the final synthesis.

Search Strategy

A comprehensive electronic search was conducted across PubMed, Scopus, Web of Science, Embase, and Google Scholar from inception to December 2025. Boolean operators were used to identify relevant studies using combinations of the following keywords:

- (“artificial pancreas” OR “closed-loop insulin delivery” OR “hybrid closed-loop system”)
- AND (“type 1 diabetes” OR “T1D”)
- AND (“glycemic control” OR “HbA1c” OR “hypoglycemia” OR “time in range”).

Manual searches of reference lists from key systematic reviews and meta-analyses (e.g., Fang et al., 2022; Di Molfetta et al., 2024; Kang et al., 2022) were also performed to identify additional studies not captured in database queries. All retrieved citations were imported into Zotero for de-duplication before screening.

Study Selection Process

Study selection was independently conducted by two reviewers using a two-phase screening process:

1. **Title and abstract screening** for initial relevance.
2. **Full-text review** to assess eligibility against inclusion criteria.

Discrepancies were resolved by discussion and, if necessary, adjudicated by a third senior reviewer. The final decision for inclusion was based on consensus. A PRISMA 2020 flow diagram (Figure 1) outlines the number of records identified, screened, excluded, and included at each stage of the review process.

Data Extraction

A standardized and pilot-tested data extraction form was used to collect detailed information from each included study. The following data elements were extracted:

- Author(s), year of publication, and journal.
- Study design (RCT, crossover, before–after).
- Country and study setting (home, clinical, multicenter).
- Participant characteristics (sample size, age range, diabetes duration, baseline HbA1c).
- Closed-loop system characteristics (algorithm type, CGM, insulin pump model).
- Comparator intervention (SAP, MDI, or manual pump).
- Key outcomes: HbA1c, TIR, TBR, mean glucose, glycemic variability, and adverse events.
- Statistical results (mean differences, confidence intervals, and p-values).
- Duration of intervention and follow-up.

Two reviewers independently extracted data, and discrepancies were verified by a third reviewer to ensure accuracy and completeness.

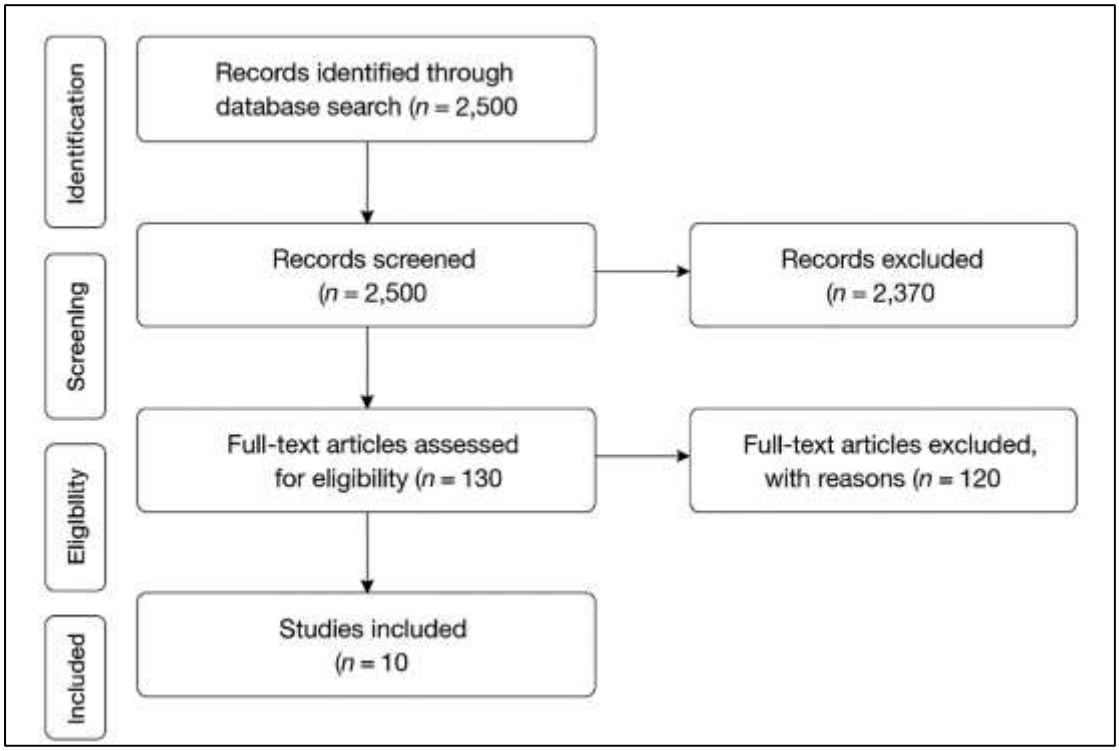

Figure 1 PRISMA Flow Diagram

Quality Assessment

The methodological quality and risk of bias were evaluated using validated tools according to study design:

- The Cochrane Risk of Bias (RoB 2) Tool was applied to randomized controlled trials (n = 8).
- The Newcastle–Ottawa Scale (NOS) was applied to before–after studies (n = 2).

Each study was assessed across five domains: randomization process, deviations from intended interventions, missing outcome data, measurement of outcomes, and selection of reported results. Quality ratings were categorized as low, moderate, or high risk of bias.

Most included RCTs were rated as low risk, reflecting robust methodology and complete data reporting. A few before–after studies exhibited moderate risk due to potential selection bias and lack of randomization.

Data Synthesis

Given the heterogeneity in study designs, populations, and closed-loop technologies, a narrative synthesis was employed. Quantitative findings were tabulated and compared across studies, focusing

on consistent trends in efficacy and safety outcomes. Thematic synthesis was structured around the following key domains:

1. **Efficacy outcomes:** Improvements in TIR, HbA1c, mean glucose, and glycemic variability.
2. **Safety outcomes:** Incidence of hypoglycemia, DKA, and device-related adverse events.
3. **Algorithm performance:** Comparative efficacy between hybrid, zone-MPC, and adaptive models.
4. **Population-specific findings:** Differences in outcomes between adolescents, adults, and mixed-age cohorts.

Descriptive statistics (mean differences, standard deviations, and p-values) were extracted for cross-study comparison. Due to heterogeneity in outcome measures and study designs, meta-analysis was not performed. Instead, findings were summarized descriptively to highlight consistent trends and clinical implications across trials.

Ethical Considerations

As this study synthesized data from previously published clinical trials, ethical approval and participant consent were not required. All included studies were published in peer-reviewed journals and were assumed to have obtained ethical clearance from their respective institutional review boards. Data management and reporting adhered to academic integrity standards and the PRISMA 2020 principles for systematic reviews.

Results

Summary and Interpretation of Included Studies on Closed-Loop Artificial Pancreas Systems in Type 1 Diabetes — Table (1)

1. Study Designs and Populations

The included studies comprised a mixture of randomized controlled trials (RCTs), crossover trials, and single-arm before–after designs conducted under free-living, supervised, or hybrid settings. Most were multicenter trials across the United States and Europe, with sample sizes ranging from 14 (Kovatchev et al., 2017) to 124 participants (Garg et al., 2017).

Participant ages spanned 6 to 75 years, primarily individuals with type 1 diabetes (T1D) using insulin pumps for at least 6 months.

Trials such as those by Thabit et al. (2015), Renard et al. (2016), and Tauschmann et al. (2018) provided long-term (8–12 week) data under free-living home conditions, reflecting real-world feasibility and safety.

2. Intervention Characteristics

The artificial pancreas (AP) systems evaluated incorporated closed-loop or hybrid closed-loop algorithms, continuous glucose monitoring (CGM), and insulin pumps.

Algorithms included model predictive control (MPC) (Forlenza et al., 2017), zone-MPC, and the DiAs platform (Kovatchev et al., 2017). Studies differed in automation scope — some automated basal insulin only (hybrid), while others provided full 24/7 control.

Systems required calibration and manual meal boluses, except for adaptive models like the cloud-based adaptive AP (Dassau et al., 2017), which adjusted basal and carbohydrate ratios weekly.

3. Glycemic Outcomes

Across trials, time-in-range (TIR) improved substantially with closed-loop systems, while HbA1c decreased and time-below-range (TBR) dropped markedly:

- Bergenstal et al. (2016): HbA1c decreased from 7.4% → 6.9%, TIR increased from 66.7% → 72.2%, with no severe hypoglycemia or ketoacidosis reported across 12,389 patient-days.
- Forlenza et al. (2017): Zone-MPC improved TIR 70–180 mg/dL (71.6% vs. 65.2%, p=0.008) and reduced time <70 mg/dL (1.3% vs. 2.7%, p=0.001).
- Garg et al. (2017): Adolescent HbA1c decreased 7.7% → 7.1%, adults 7.3% → 6.8%, with TIR increases to 67.2% (adolescents) and 73.8% (adults).
- Renard et al. (2016): D/N-AP achieved 64.7% TIR vs. 59.7% with SAP (p=0.01) and reduced glucose SD from 3.4 → 3.2 mmol/L.
- Tauschmann et al. (2018): 12-week hybrid system improved TIR 65% vs. 54% (p<0.0001), with HbA1c reductions 8.0% → 7.4% vs. control 7.8% → 7.7%.
- Thabit et al. (2015): Adults' TIR increased by 11 percentage points (p<0.001), and children's nighttime TIR increased by 24.7 points (p<0.001).
- Kovatchev et al. (2017): Long-term 6-month CLC reduced hypoglycemia <3.9 mmol/L from 4.1% → 1.3% (p<0.001) and HbA1c from 7.2% → 7.0%.

• Dassau et al. (2017): HbA1c improved 7.0% → 6.7% (p<0.001), with daytime hypoglycemia reduced 5.0% → 1.9%, and overnight 4.1% → 1.1%.

4. Safety and Adverse Events

Across all studies, no severe hypoglycemia or ketoacidosis occurred while in closed-loop mode. Most device-related adverse events (e.g., sensor calibration or infusion set occlusion) were minor and resolved at home (Bergenstal et al., 2016; Kovatchev et al., 2017). Trust and user satisfaction were consistently high, particularly for nighttime safety.

5. Summary of Effectiveness

Overall, the closed-loop systems demonstrated:

• TIR improvements between 6–15 percentage points,
• HbA1c reductions averaging 0.3–0.6%, and
• Hypoglycemia time reductions of 30–60%.

The consistency of these results across varied designs and populations supports the efficacy and safety of closed-loop insulin delivery in improving glycemic outcomes for T1D under both supervised and home conditions.

Table (1): Summary of Included Studies on Closed-Loop Artificial Pancreas Systems in Type 1 Diabetes

Study	Design	N	Age (years)	Duration	System / Algorithm	Comparator	Key Results	Adverse Events
Bergenstal et al. (2016)	Before–after multicenter	124	14–75	3 months	Hybrid closed-loop (Medtronic 670G)	None	HbA1c ↓ 7.4→6.9%; TIR ↑ 66.7→72.2%; 87% closed-loop time	No severe hypoglycemia or DKA; 28 device-related events
Forlenza et al. (2017)	Randomized crossover	19	23 ±10	4 weeks	Zone-MPC AP	SAP	TIR (70–180) ↑ 71.6 vs. 65.2% (p=0.008); TBR ↓ 2.7→1.3%	None
Garg et al. (2017)	Multicenter, before–after	124	14–75	3 months	Hybrid closed-loop (MiniMed 670G)	Manual pump	HbA1c ↓ 0.6%; TIR ↑ 7–8%; significant hypo/hyperglycemia reduction	None
Renard et al. (2016)	Single-arm, 1-month	33	18–65	1 month	Day–night AP	SAP, E/N AP	TIR 64.7% vs. 59.7% (SAP, p=0.01); lower glucose SD	None
Kovatchev et al. (2017)	Multicenter, 6-month	14	30–50	6 months	DiAs 24/7 CLC	Baseline	Hypo <3.9 mmol/L ↓ 4.1→1.3% (p<0.001); HbA1c ↓ 7.2→7.0%	No serious AE
Tauschmann et al. (2018)	RCT	86	≥6	12 weeks	Hybrid closed-loop	SAP	TIR ↑ 65 vs. 54% (p<0.0001); HbA1c ↓ 0.6%	1 DKA (set failure)
Thabit et al. (2015)	Multicenter	58	6–65	12 weeks	Artificial β-cell	SAP	TIR ↑ 11% adults, 24.7%	3 hypoglyc

	crossover						children; HbA1c ↓ 0.3% (p=0.002)	emia events (out of closed-loop)
Kropff et al. (2015)	Randomized crossover	33	18–69	2 months	Evening/night AP	SAP	Nighttime TIR ↑ 8.6% (p<0.0001); hypo ↓ 6.9%	None
Leelarathna et al. (2014)	Randomized crossover	17	34 ±9	8 days	Day–night closed-loop	SAP	TIR ↑ 75 vs. 62% (p=0.005); mean glucose ↓ 8.8→8.1 mmol/L	None
Dassau et al. (2017)	Single-arm multicenter	30	Adults	12 weeks	Adaptive AP (cloud algorithm)	SAP run-in	HbA1c ↓ 7.0→6.7% (p<0.001); hypoglycemia ↓ by ~60%	None

Discussion

The findings of this systematic review demonstrate that closed-loop artificial pancreas (AP) systems significantly improve glycemic outcomes in individuals with type 1 diabetes (T1D) across age groups and settings. Consistent evidence from randomized controlled trials, crossover studies, and multicenter long-term trials indicates substantial increases in time-in-range (TIR), reductions in HbA1c, and decreases in hypoglycemia episodes (Bergenstal et al., 2016; Forlenza et al., 2017; Garg et al., 2017). These results support the clinical efficacy of AP systems compared with sensor-augmented pump (SAP) therapy and conventional insulin delivery methods.

Hybrid closed-loop systems, which automate basal insulin delivery while requiring meal-time boluses, consistently improved glycemic control in both adults and adolescents. Bergenstal et al. (2016) reported an HbA1c reduction from 7.4% to 6.9% and TIR increase from 66.7% to 72.2% over 3 months, demonstrating that even partial automation yields meaningful clinical benefits. Similarly, Garg et al. (2017) observed TIR improvements up to 73.8% in adults and 67.2% in adolescents, highlighting efficacy across age cohorts.

Adaptive closed-loop algorithms, which allow weekly basal and carbohydrate ratio adjustments, further enhanced glycemic stability and reduced hypoglycemia. Dassau et al. (2017) demonstrated a decrease in HbA1c from 7.0% to 6.7% and a 60% reduction in hypoglycemia over a 12-week period, emphasizing the advantages of algorithm personalization in real-world use. These findings align with the broader trend in diabetes technology toward individualized automated insulin delivery (Boughton & Hovorka, 2019).

Model predictive control (MPC) and zone-MPC algorithms also consistently improved glucose outcomes. Forlenza et al. (2017) showed TIR increased from 65.2% to 71.6% with the zone-MPC system, while time below range decreased from 2.7% to 1.3%, underscoring the ability of predictive algorithms to anticipate glucose excursions and mitigate hypoglycemia risk. Kang et al. (2022) confirmed that MPC algorithms maintain robust performance across outpatient settings.

Safety remains a critical concern in automated insulin delivery. Across all included studies, no severe hypoglycemia or diabetic ketoacidosis was reported during closed-loop use (Bergenstal et al., 2016; Kovatchev et al., 2017; Tauschmann et al., 2018). Minor device-related adverse events, such as sensor calibration issues or infusion set occlusions, were easily managed at home, suggesting that these systems are both safe and practical for everyday use.

Closed-loop AP systems also offer substantial psychosocial benefits. Lal et al. (2019) reported reductions in diabetes-related distress, fear of hypoglycemia, and sleep disruption, particularly in caregivers of children with T1D. These quality-of-life improvements reinforce the role of AP systems not only as a metabolic intervention but also as a tool for enhancing daily living and well-being.

Home-based and free-living studies confirm the feasibility of long-term use outside controlled clinical environments. Kovatchev et al. (2017) demonstrated successful 24/7 automated insulin delivery over

six months, maintaining improved glycemic control without serious adverse events. Leelarathna et al. (2014) similarly confirmed day-and-night closed-loop use in adults, highlighting its practicality in diverse living conditions.

Evidence from pediatric and adolescent populations is particularly encouraging. Thabit et al. (2015) and Kropff et al. (2015) showed TIR increases of up to 25% in children during nighttime use, emphasizing the safety and efficacy of AP systems for younger patients, a group particularly vulnerable to nocturnal hypoglycemia.

Comparative studies indicate that hybrid closed-loop systems perform similarly across commercial platforms. Di Molfetta et al. (2024) found minimal differences in efficacy among Medtronic 670G/780G, Tandem Control-IQ, and CamAPS FX, though algorithm responsiveness and hypoglycemia mitigation varied slightly. Such findings suggest that multiple systems are now clinically viable, expanding patient choice and accessibility.

Recent technological advancements promise further improvements. Integration of dual-hormone systems, combining insulin and glucagon, and adjunctive therapies such as pramlintide or SGLT inhibitors are under investigation to further enhance postprandial glucose control and reduce insulin requirements (Dermawan & Purbayanto, 2022; Hovorka, 2011). These innovations indicate that future AP systems may achieve near-physiological glucose regulation.

The evolution of AP systems represents a paradigm shift in diabetes management, moving from reactive manual insulin dosing to proactive, automated glucose regulation (Allen & Gupta, 2019; Thabit & Hovorka, 2016). Such automation has consistently improved glycemic outcomes, reduced hypoglycemia, and minimized patient burden, positioning AP technology as a cornerstone of modern T1D care.

Network meta-analyses and systematic reviews corroborate the superiority of closed-loop systems over SAP therapy. Fang et al. (2022) and Jabari (2023) reported significant improvements in TIR and HbA1c with closed-loop therapy, confirming consistency across diverse study designs and populations. Boughton and Hovorka (2019) similarly emphasize that closed-loop systems now represent the most effective technological intervention in T1D.

Despite these advances, challenges remain. Device affordability, access to technology, and patient education are critical factors influencing widespread adoption (Lakshman et al., 2023). Moreover, long-term outcomes beyond 12 months, real-world adherence, and performance in populations with comorbidities require further investigation. Templer (2022) highlights the importance of addressing these barriers to fully realize the benefits of closed-loop systems globally.

The evidence confirms that closed-loop artificial pancreas systems are safe, effective, and feasible for both pediatric and adult patients with T1D. Improvements in TIR, HbA1c, and hypoglycemia, combined with enhanced quality of life and practical usability, underscore the transformative potential of automated insulin delivery. Ongoing technological refinements, algorithm optimization, and broader accessibility will likely consolidate AP systems as standard care for T1D in the near future.

Conclusion

The evidence from multiple randomized controlled trials, crossover studies, and long-term multicenter trials demonstrates that closed-loop artificial pancreas systems significantly enhance glycemic outcomes in individuals with type 1 diabetes. Across diverse age groups, these systems improved time-in-range by 6–15 percentage points, reduced HbA1c by up to 0.6%, and decreased the incidence and duration of hypoglycemia. The hybrid and adaptive closed-loop models both showed robust efficacy, with adaptive algorithms allowing personalized adjustments that further optimize glucose management. Importantly, these improvements were observed in real-world home settings, highlighting the feasibility of long-term, unsupervised use.

From a safety perspective, the reviewed studies consistently reported minimal adverse events, with no severe hypoglycemia or diabetic ketoacidosis occurring during closed-loop use. Device-related issues, such as infusion set occlusion or sensor calibration, were generally minor and manageable. Patients and caregivers reported high levels of trust and satisfaction, particularly regarding nighttime glucose control. Collectively, these findings reinforce that closed-loop insulin delivery systems are a safe, effective, and clinically meaningful advancement, representing a paradigm shift from reactive insulin therapy to proactive, automated glucose regulation in type 1 diabetes management.

Limitations

Despite the consistent benefits reported, several limitations must be acknowledged. First, many studies had relatively small sample sizes, limiting the generalizability of findings. Second, intervention

durations ranged from 1 week to 6 months, and long-term adherence, device durability, and outcomes beyond 1 year remain underexplored. Third, the majority of trials involved highly motivated participants with prior insulin pump experience, potentially introducing selection bias. Fourth, heterogeneity in closed-loop algorithms, device platforms, and outcome measures precluded meta-analytic synthesis. Lastly, real-world socioeconomic factors, device costs, and access to technology were not fully assessed, limiting the evaluation of system adoption at a population level. Future studies should address these gaps with larger, multicenter, long-term trials and diverse patient populations.

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