Research Article

INNOVATIONS AND RECENT PROGRESS IN AUTOMATED THERAPEUTIC DELIVERY SYSTEM

[1*]Vikas Selvam S, [2]Saalini Vellivel, [3]Kiran Kumar S, [4]Sibi S and [5]Sujitha K

[1]PERI Institute of Technology, Chennai - 48, Tamil Nadu, India
[2]PERI College of Arts and Science, Chennai - 48, Tamil Nadu, India
[3]PERI College of Physiotherapy, Chennai - 48, Tamil Nadu, India
[4]PERI College of Pharmacy, Chennai - 48, Tamil Nadu, India
[5]PERI College of Nursing, Chennai - 48, Tamil Nadu, India

ABSTRACT

Automated therapeutic delivery systems have significantly transformed modern healthcare by enabling precise, controlled, and patient-specific administration of medications. Recent advancements in sensing technologies, artificial intelligence (AI), microfluidics, and biomedical engineering have driven the development of intelligent platforms capable of optimizing drug dosage, timing, and delivery routes with minimal human intervention. These systems aim to enhance therapeutic outcomes, reduce clinical errors, and improve patient compliance across diverse medical domains such as diabetes care, oncology, pain management, cardiovascular treatment, and critical care. This study provides a comprehensive review of recent innovations in automated drug delivery mechanisms, including closed-loop systems, wearable and implantable devices, smart pumps, and AI-assisted delivery models. The paper highlights emerging trends, technological enablers, and system architectures, followed by an analysis of current limitations, safety considerations, and future research trajectories. The findings emphasize the growing role of automation in personalized medicine and its potential to redefine treatment paradigms in both clinical and home-care environments.

Keywords: Automated drug delivery**,** Therapeutic delivery systems**,** Smart infusion pumps, Closed-loop systems.

INTRODUCTION

The demand for efficient, precise, and responsive therapeutic delivery mechanisms has increased substantially with the growing global burden of chronic and acute medical conditions. Traditional drug administration often relies on manual intervention, which is susceptible to inaccuracies, fluctuating therapeutic levels, and reduced patient adherence. Automated therapeutic delivery systems have emerged as a transformative solution, enabling continuous monitoring, feedback-controlled dosing, and optimized drug release tailored to individual physiological conditions. Automation in drug delivery systems has expanded across several healthcare sectors. In diabetes management, for example, closed-loop insulin delivery systems integrate glucose sensors with control algorithms to maintain optimal blood glucose levels without frequent patient input (Templer, 2022). Similarly, oncology has benefited from programmable infusion pumps that deliver chemotherapeutic agents with enhanced precision, reducing systemic toxicity. Recent innovations in wearable and implantable drug delivery platforms have further broadened the scope of personalized and remote healthcare.

Technological advancements such as microelectromechanical systems (MEMS), Internet of Things (IoT) connectivity, artificial intelligence, biocompatible materials, and microfluidics have catalyzed the development of next-generation automated delivery devices. These innovations enable real-time physiological data acquisition, precise payload control, predictive analytics, and adaptive drug release mechanisms (Serrano, 2024). As healthcare transitions toward more patient-centric and data-driven models, automated therapeutic

---

*Corresponding Author: Vikas Selvam S, PERI College of Physiotherapy,
Chennai – 48, Tamil Nadu, India Email : publications@peri.ac.in

481

delivery systems are becoming integral components of modern treatment strategies. Despite these advancements, several challenges persist, including device reliability, long-term biocompatibility, cybersecurity threats, and regulatory constraints. Understanding recent progress, design methodologies, and practical limitations is essential for guiding future innovations and improving clinical adoption. Recent reviews highlight a shift from prototype research toward clinically validated, user-centered systems and broader adoption in both hospital and home-based care environments (Templer, 2022). Closed-loop insulin delivery (also known as automated insulin delivery or artificial pancreas systems) remains the most mature domain of automated therapeutics. Hybrid closed-loop systems that combine continuous glucose monitors (CGMs), insulin pumps, and control algorithms have consistently demonstrated improved Time-In-Range (TIR) and reduced hypoglycemia across multiple clinical trials and meta-analyses (Fan, 2024). Ongoing work now focuses on fully closed-loop mealtime control, multi-hormone delivery approaches, sensor accuracy, and long-term user acceptability (Templer, 2022).
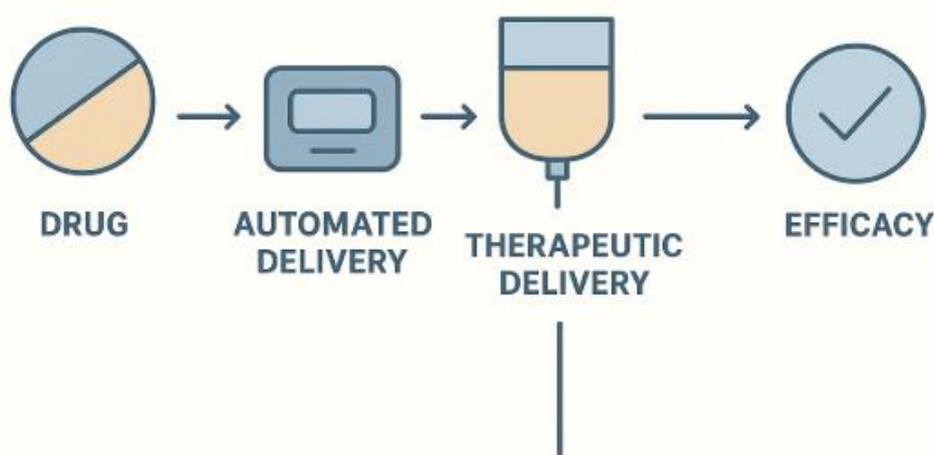

Figure 1. Innovations and Recent Progress in Automated Therapeutic Delivery System.

Smart infusion pumps (with drug libraries, Dose Error Reduction Systems—DERS, and interoperability features) have reduced some medication-administration errors, but human factors, outdated libraries, and integration gaps remain important causes of residual errors. Recent evaluations recommend tighter interoperability between EHRs and pumps, improved usability testing, and continuous library management to fully realize safety benefits (Alamer, 2023; Herrero, 2025). Wearable patch pumps and implantable infusion devices have expanded automated delivery beyond hospitals into ambulatory and home care. Recent work investigates miniaturized reservoirs, programmable micro-actuators, and long-term biocompatibility. Patch pumps show promise for insulin and pain medications, whereas implantables are being explored for chemotherapy, chronic pain, and hormone delivery, with emphasis on refillability and infection control (Rimon, 2024; Hughes, 2025). Microneedle (MN) platforms (solid, coated, dissolving, hollow) are a major innovation enabling minimally invasive, potentially self-administered, and programmable transdermal drug delivery. Reviews from 2000-2025 summarize progress in materials, fabrication techniques, and clinical translation, highlighting MNs' potential for vaccine and biologic delivery, sustained release, and integration with wearable controllers for on-demand dosing (Cammarano, 2024; Maia, 2025). Remaining challenges include manufacturing scale-up, sterility assurance, skin variability, and regulatory pathways. Microfluidic and MEMS approaches enable precise metering, mixing, and multi-reservoir dosing at small scales, supporting programmable release profiles and multiplexed therapy (e.g., combination chemotherapy, on-demand analgesia). Reviews argue that microfabrication and lab-on-a-chip technologies are enabling more complex closed-loop architectures, though reliability, clogging, and long-term operation require further engineering validation (Alémán, 2025).

AI and machine learning enhance personalization through patient-specific PK/PD models, predictive dosing, anomaly detection (e.g., sensor drift, occlusions), and adaptive controller design. Recent reviews show AI's growing role in optimizing formulations, predicting release kinetics, and refining closed-loop controller performance; however, data quality, explainability, and regulatory acceptance remain major barriers to widespread clinical deployment (Serrano, 2024; Joshi, 2025). Additive manufacturing enables on-demand, patient-specific dosage forms and complex multidrug geometries that can be integrated with electronic elements for programmable release (such as printed

reservoirs or embedded microcontrollers). Reviews highlight several proof-of-concept and early clinical translation examples but emphasize scale-up, stability, and dose-accuracy concerns as major hurdles for routine clinical use (Serrano, 2024).

Safety remains central: while automated systems can reduce certain errors, they also introduce new failure modes, including algorithm faults, sensor drift, and cybersecurity risks. Human-factors studies repeatedly call for co-design with clinicians and patients, robust verification and validation, transparent alarm schemes, and regulatory frameworks that adequately address software-as-a-medical-device (SaMD) considerations (Herrero, 2025; Alamer, 2023). Interoperability standards (IHE, HL7/FHIR) and up-to-date drug libraries are practical necessities. Major gaps persist, including long-term sensor reliability, secure connectivity, explainability of AI controllers, scalable manufacturing of components such as microneedles and microfluidics, and harmonized regulatory pathways for systems that integrate hardware, software, and biologic elements. Promising development directions include multimodal sensing (e.g., biomarker panels), multimodal delivery (multi-reservoir pumps, multi-hormone systems), AI-enabled predictive maintenance, and connected wearable-to-cloud ecosystems for remote clinical oversight (Hughes, 2025; Panchpuri, 2025).

MATERIALS AND METHODS

This study adopts a structured review methodology to analyze recent advancements in automated therapeutic delivery systems. The approach integrates systematic search procedures, inclusion and exclusion criteria, and thematic synthesis to ensure a comprehensive and unbiased assessment. A systematic search was conducted across Scopus, PubMed, IEEE Xplore, ScienceDirect, and Web of Science databases. Keywords used included: "automated drug delivery," "therapeutic delivery systems," "closed-loop delivery," "smart infusion pumps," "wearable drug delivery," "AI-based drug administration," and "microfluidic drug delivery." Boolean operators (AND/OR) were applied to refine the results. Articles published between 2020 and 2025, Peer-reviewed journal articles, systematic reviews, meta-analyses, and high-quality conference papers. Studies focusing on innovation, automation, sensing integration, AI, or precision mechanisms in drug delivery. Papers describing clinical trials, prototype systems, or validated experimental models' non-English publications. Papers without methodological clarity. Studies limited to traditional/manual drug delivery approaches. Articles with insufficient data or non-scientific content Selected studies were analyzed based on: Type of automated system (closed-loop, wearable, implantable, pump-based, AI-assisted). Core technologies (sensors, MEMS, IoT, microfluidics). Performance metrics (accuracy, responsiveness, safety outcomes, usability). Clinical utility and regulatory implications. Findings were organized into key themes to provide a topic-wise narrative covering current innovations and challenges.

RESULTS AND DISCUSSION

Closed-loop delivery has shown significant improvements in precision and real-time adaptability. Systems like automated insulin delivery demonstrate increased time-in-range (TIR), reduced hypoglycemia, and improved patient autonomy. Similar principles are being translated to pain management, anesthesia, and oncology drug delivery. Smart pumps with drug libraries, dose error reduction systems (DERS), and electronic health record (EHR) interoperability have reduced medication errors in hospital settings. Wearable patch pumps, implantable micro-reservoir systems, and programmable injection devices support long-term therapy management across diabetes, hormonal therapies, and analgesia. Microneedles enable minimally invasive and pain-free delivery of vaccines, peptides, and biological drugs. Automated microneedle systems integrated with wearable platforms have demonstrated controlled, programmable transdermal release. Microfluidic chips and MEMS actuators enable ultra-precise dosing, multiplexed therapy, and self-regulating release profiles.AI-driven prediction models, adaptive dosing controllers, and anomaly detection mechanisms enhance safety and personalization. Automated systems reduce manual errors but introduce new risks, such as cyber-vulnerabilities and algorithm failure.

These systems represent one of the most mature innovations, but sensor reliability, calibration needs, and algorithm transparency remain critical challenges. Despite improvements, user interface complexity and outdated drug libraries still contribute to programming errors. Integration of AI-driven alerts and better human-factor design can further enhance safety. These systems improve mobility and comfort, but concerns regarding biocompatibility, long-term durability, and infection control must be addressed through material innovations and improved sealing technologies. Although promising for self-administered therapy, scalability and regulatory validation pose significant barriers. MEMS systems provide high accuracy but face reliability issues such as clogging and long-term consistency in biological environments. can significantly improve system intelligence, but transparency, explainability, and compliance with software-as-a-medical-device (SaMD) regulations remain unresolved issues. Regulatory frameworks are evolving but still lag behind rapid technological advancements. Multi-layered safety verification and user-centered design are essential.

CONCLUSION

Automated therapeutic delivery systems have advanced considerably due to technological innovations in sensors, AI, microfluidics, wearable electronics, and biocompatible materials. These systems enhance precision, patient autonomy, and overall therapeutic outcomes while reducing human error in clinical and home-based settings. The integration of real-time monitoring, adaptive algorithms, and automated actuation makes these systems central to the advancement of personalized medicine. However,

challenges persist in areas such as long-term biocompatibility, system reliability, cybersecurity, interoperability, and regulatory compliance. While innovations continue at a rapid pace, a comprehensive approach combining engineering robustness, clinical validation, user-centered design, and regulatory harmonization is essential for large-scale adoption.

ACKNOWLEDGMENT

CONFLICT OF INTERESTS

The authors declare no conflict of interest

ETHICS APPROVAL

Not applicable

FUNDING

AI TOOL DECLARATION

The authors declares that no AI and related tools are used to write the scientific content of this manuscript.

DATA AVAILABILITY

Data will be available on request

REFERENCES

Zafar, S., Rana, S. J., Hamza, M., & Others. (2025). *Advancements in transdermal drug delivery using microneedles: Technological and material perspective.* Discover Pharmaceutical Sciences, 1, 5.

Xiong, X., (2025). *Recent advances and perspectives of microneedles for biomedical applications.* Biophysical Reviews, 17, 909–928.

Economidou, A., Lamprou, D. A., McDonald, J., Bathgate, S., & Douroumis, D. (2024). *A novel integrated transdermal drug delivery system with micropump and microneedle made from polymers.* Micromachines, 14(1), 71.

Luo, X., Yu, Q., Yang, L., Cui, Y., & Liu, Y. (2024). *A wearable, rapidly manufacturable, stability-enhancing microneedle patch for closed-loop diabetes management.* Microsystems & Nanoengineering, 10, 112.

Larrañeta, E., et al. (2024). *Wearable and implantable devices for drug delivery: Applications and challenges.* Biomaterials, 283, 121435.

Rimon, M. T. I., Hasan, M. W., Hassan, M. F., & Cesmeci, Ş. (2024). *Advancements in insulin pumps: A comprehensive exploration of insulin pump systems, technologies and future directions.* Pharmaceutics, 16(7), 944.

Díaz-Balzac, C. A. (2022). *Continuous subcutaneous insulin infusions: Closing the loop.* The Journal of Clinical Endocrinology & Metabolism, 108(5), 1019–1028.

Manikkath, J., & Subramony, J. A. (2021). *Toward closed-loop drug delivery: Integrating wearable technologies with transdermal drug delivery systems.* Advanced Drug Delivery Reviews, 179, 113997. https://doi.org/10.1016/j.addr.2021.113997

Cammarano, A., Dello Iacono, S., Battisti, M., De Stefano, L., Meglio, C., & Nicolais, L. (2024). *A systematic review of microneedles technology in drug delivery through a bibliometric and patent overview.* Heliyon, 10(23), e40658. https://doi.org/10.1016/j.heliyon.2024.e40658

Apoorva, S., Nguyen, N.-T., & Sreejith, K. R. (2024). *Recent developments and future perspectives of microfluidics and smart technologies in wearable devices.* Lab on a Chip, 24, 1833–1866. https://doi.org/10.1039/D4LC00089G

Fan, W., Deng, C., Xu, R., Liu, Z., Leslie, R. D., & Zhou, Z. (2024). *Efficacy and safety of automated insulin delivery systems in patients with type 1 diabetes mellitus: A systematic review and meta-analysis.* Diabetes & Metabolism Journal. Advance online publication. https://doi.org/10.4093/dmj.2024.0130

Domingo-Lopez, D. A., Lattanzi, G., Schreiber, L. H. J., Wallace, E. J., Wylie, R., O'Sullivan, J., Dolan, E. B., & Duffy, G. P. (2022). *Medical devices, smart drug delivery, wearables and technology for the treatment of diabetes mellitus.* Advanced Drug Delivery Reviews, 185, 114280. https://doi.org/10.1016/j.addr.2022.114280

Liu, Y., Yu, Q., Ye, L., Yang, L., & Cui, Y. (2023). *A wearable, minimally-invasive, fully electrochemically-controlled feedback minisystem for diabetes management.* Lab on a Chip, 23(3), 421–436. https://doi.org/10.1039/D2LC00797E