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IMPLANTABLE INSULIN DELIVERY SYSTEMS AND WEARABLE GLUCOSE MONITORING TECHNOLOGIES: CURRENT ADVANCES AND FUTURE PERSPECTIVES IN DIABETES MANAGEMENT

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Abstract:
Diabetes mellitus is a chronic metabolic disorder characterized by persistent hyperglycaemia resulting from defects in insulin secretion, insulin action, or both. Effective glycemic control is essential to prevent long-term complications such as cardiovascular diseases, neuropathy, nephropathy, and retinopathy. Conventional insulin delivery methods, including multiple daily injections and external insulin pumps, have improved diabetes management; however, these approaches are often associated with limitations such as patient discomfort, inconsistent insulin absorption, risk of hypoglycemia, and poor treatment adherence. To overcome these limitations, implantable insulin delivery systems have emerged as an innovative approach for achieving more precise and physiological insulin administration. These devices provide continuous and controlled insulin release directly within the body and typically consist of an insulin reservoir, pumping mechanism, catheter, and programmable control unit. Recent technological advancements include implantable insulin pumps, closed-loop artificial pancreas systems, and bioartificial pancreas models integrating continuous glucose monitoring with automated insulin delivery. Additionally, emerging strategies involving nanotechnology, glucose-responsive biomaterials, and smart insulin formulations are being explored to enhance efficiency and safety. These advanced systems improve glycemic regulation, reduce injection burden, and enhance patient compliance. Despite promising benefits, challenges such as surgical risks, device malfunction, infection, high cost, and long-term biocompatibility concerns remain. Future developments focusing on miniaturization, automation, advanced sensing technologies, and stem cell-derived beta-cell implants may transform diabetes therapy. Overall, implantable insulin delivery systems represent a significant advancement toward achieving improved glycemic control and improving the quality of life for individuals living with diabetes.

Keywords: *Implantable insulin pump, Artificial intelligence, Smart drug delivery, Diabetes management.*

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1. INTRODUCTION:

Diabetes mellitus is a serious chronic metabolic disorder characterized by elevated blood glucose levels resulting from either insufficient insulin production by the pancreas or the inability of the body to effectively utilize insulin. Among the different types, Type 2 diabetes mellitus (T2DM) accounts for approximately 90% of all diagnosed cases of diabetes in adults[1]. It is the most common form of diabetes and is often referred to as adult-onset or non–insulin-dependent diabetes1. T2DM generally develops gradually over time and is frequently associated with insulin resistance and impaired insulin secretion. Although it is considered a milder form during early stages and can often be managed with diet and oral hypoglycemic agents, uncontrolled or untreated T2DM can lead to severe complications similar to those observed in Type 1 diabetes[2].The exact cause of diabetes mellitus remains unclear; however, both genetic predisposition and environmental factors play significant roles in its development. This rising incidence is attributed to rapid socio-cultural changes, ageing populations, urbanization, reduced physical activity, and unhealthy lifestyle patterns[3].

2. Classifications of Diabetes Mellitus

Diabetes is a heterogeneous complex metabolic disorder characterized by elevated blood glucose concentration secondary to either resistance to the action of insulin, insufficient insulin secretion, or both . The major clinical manifestation of the diabetic state is hyperglycemia. However, insulin deficiency and/or insulin resistance also are associated with abnormalities in lipid and protein metabolism, and with mineral and electrolyte disturbances. The vast majority of diabetic patients are classified into one of two broad categories: type 1 diabetes mellitus, which is caused by an absolute or near absolute deficiency of insulin, or type 2 diabetes mellitus, which is characterized by the presence of insulin resistance with an inadequate compensatory increase in insulin secretion[5]. In addition, women who develop diabetes during their pregnancy are classified as having gestational diabetes. Finally, there are a variety of uncommon and diverse types of diabetes, which are caused by infections, drugs, endocrinopathies, pancreatic destruction, and genetic defects. These unrelated forms of diabetes are included in the "Other Specific Types" and classified separately[4].

Table 1 Etiologic Classification of Diabetes Mellitus

I	Type 1 diabetes (beta-cell destruction, usually leading to absolute insulin deficiency) 1. Immune mediated 2. idiopathic
II	Type 2 diabetes (May range from predominantly insulin resistance with relative insulin deficiency to a predominantly insulin secretory defect with insulin resistance)
III	Gestational diabetes mellitus (GDM)
IV	Other specific types

1. Pathophysiological Aspects

Type 2 diabetes mellitus is characterized by insulin insensitivity resulting from insulin resistance, progressive decline in insulin production, and eventual pancreatic β-cell failure. This leads to reduced glucose uptake in the liver, skeletal muscle, and adipose tissue. In addition, increased lipolysis contributes to elevated free fatty acid levels and worsening hyperglycemia [6].

Type 1 diabetes mellitus commonly occurs in children and adolescents and is typically associated with autoimmune destruction of pancreatic β-cells. Individuals often have a genetic predisposition, with an increased incidence observed among first-degree relatives and strong associations with specific human leukocyte antigen (HLA) types. Environmental factors such as viral infections may trigger immune-mediated damage to β-cells, initiating an autoimmune process. Clinical diabetes becomes evident when approximately 80–90% of β-cells are destroyed, resulting in absolute insulin deficiency [7]. Insulin deficiency may also affect neuronal function by impairing long-term potentiation, potentially leading to deficits in learning and memory [8].

Furthermore, insulin resistance has been linked to neurodegenerative changes, including amyloid-β (Aβ) plaque formation and tau hyperphosphorylation. During hyperinsulinemia, insulin and Aβ compete for the insulin-degrading enzyme, leading to accumulation of Aβ and subsequent plaque formation. Reduced insulin receptor signaling decreases Akt activity and activates glycogen synthase kinase-3β (GSK-3β), which contributes to tau hyperphosphorylation and neuronal dysfunction [9].

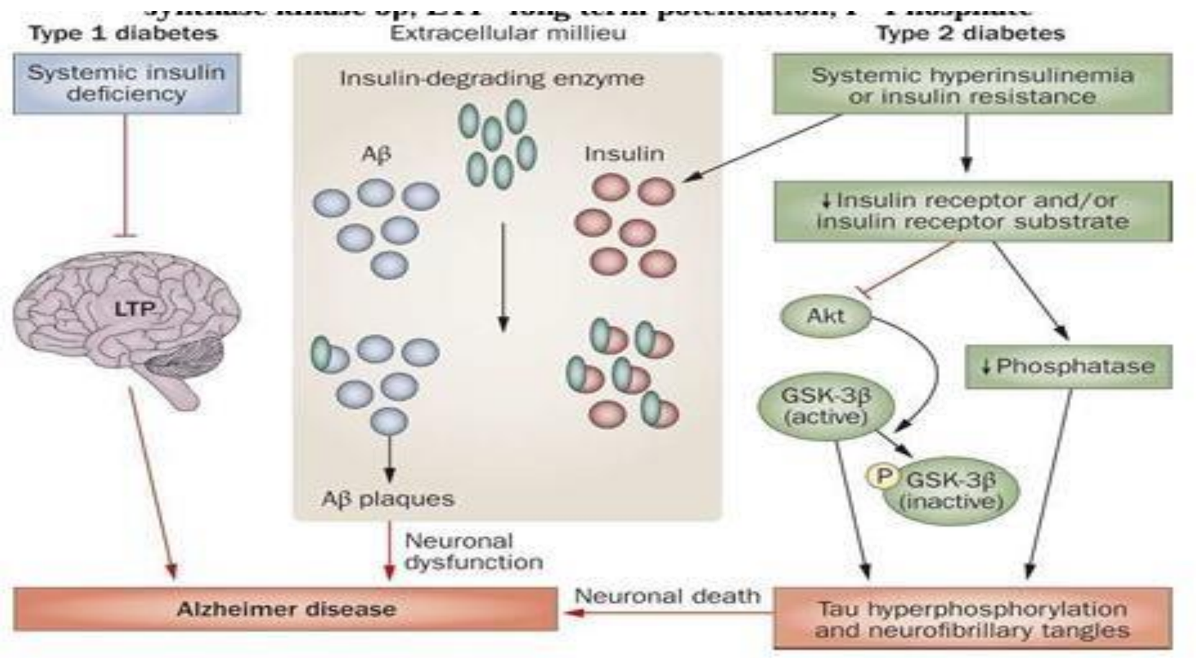


Figure 1: Pathophysiology of Type 1 and Type 2 diabetes. Abbreviations: Aβ, amyloid-β; GSK-3β, glycogen synthase kinase-3β; LTP, long-term potentiation; P, phosphate.

2. *Implantable drug delivery system*

Implantable drug delivery systems (IDDS) are devices that are inserted under the skin or within body tissues to enable a controlled and prolonged release of therapeutic agents over time, eliminating the need for repeated needle injections. These systems generally consist of a drug reservoir, a rate-controlling membrane or matrix, and structural support that facilitates the gradual release of medication into the bloodstream[10]. Implantable devices are especially beneficial for managing chronic conditions that require long-term treatment. While oral administration is the most common method for delivering drugs, it has several drawbacks, including drug degradation in the gastrointestinal tract, first-pass metabolism, inconsistent absorption, and poor patient adherence. Although intravenous administration is effective, it can lead to fluctuating plasma drug levels and a higher risk of toxicity. To address these issues, controlled drug delivery methods like implantable systems have been developed. These devices offer continuous, predictable, and targeted drug release, maintaining therapeutic drug levels and reducing side effects[11]. Implantable systems can be broadly categorized into polymeric drug implants and implantable mini-pumps. Polymeric implants can be either biodegradable or non-biodegradable and come in various forms such as rods, cylinders, rings, and films. Implantable mini-pumps deliver drugs through osmotic, mechanical, or programmable mechanisms. These devices are typically placed subcutaneously in the upper arm, abdomen, or thigh, and in some cases, they may be surgically implanted in specific body areas like the intraperitoneal cavity or the intravitreal region of the eye. Implantable drug delivery systems are particularly advantageous for chronic diseases that require sustained and controlled drug administration[12].

3. Ideal properties of implantable drug delivery system

- Improve patient compliance by reducing the dosing frequency during the therapy.
- It should release the drug in a controlled manner and to maintain a drug level in the therapeutic range thus reducing side effects.
- It should allow easy termination of the therapy by a medical practitioner. • It should be and safe and stable with good mechanical strength.
- It should be easily sterilized
- It should be economical and easy to manufacture. It should not present any medical complication.
- It should be biocompatible.
- It should be chemically inert, non-carcinogenic and hypoallergenic in nature[15].
- The implant should be easily removable by medicinal personnel to discontinue treatment[13].

4. Advantages and disadvantages of implantable drug delivery system

➢ Advantages

- Targeted drug Delivery can achieve by the implantable drug delivery system.
- Improved patient compliance.
- Reduced wastage of the drug.
- Improved efficiency.
- Minimum dose is required.
- Reduced side effects.
- Convenient therapy.
- Provide continuous sustained drug discharge over extended duration
- Avoid the first pass metabolism.
  Improved bioavailability

➢ Disadvantages

- Interactions between host and implant.
- Insertion of big size implants requires surgical
- Interventions which can be unpleasant.
- Treatment cannot be abruptly stopped.
- Possibility of inadequate release of drug.
- Predicted danger of device failure.
- Chances of adverse reactions due to the local high
- Concentration of drug at site of implantation[14].

5. Implantable drug delivery system for insulin

Overview of Insulin Delivery Approaches

Overview of Insulin Delivery Methods Traditional diabetes management strategies encompass oral hypoglycemic medications, insulin shots, insulin infusion devices, and pancreas transplants. While oral antidiabetic medications are frequently prescribed for early-stage type 2 diabetes, they demand strict compliance and can lead to gastrointestinal issues. For individuals with type 1 diabetes and advanced type 2 diabetes, external insulin administration is essential to maintain normal blood sugar levels[15]. Standard insulin delivery techniques, such as multiple daily injections and external insulin pumps, offer therapeutic advantages but come with drawbacks like fluctuating glucose levels, patient discomfort, and low adherence. These challenges have spurred the creation of advanced insulin delivery systems, including implantable pumps, glucose-responsive biomaterials, microneedle-based systems, and bioartificial pancreas technologies, all aimed at achieving sustained and physiological insulin release .Image Figure 2. Graphical representation of traditional, novel, and future insulin delivery methods Implantable Insulin Pumps Insulin Pumps Insulin pumps are medical devices that continuously supply insulin from a reservoir to individuals with diabetes, aiding in the maintenance of stable blood glucose levels. There are three primary types of insulin pumps: Traditional insulin pumps Insulin patch pumps Implantable insulin pumps (as shown in Figure 2) .Traditional Insulin Pumps Traditional insulin pumps comprise a wearable main unit, tubing, and an infusion cannula (Figure 3a). The main unit houses an insulin reservoir, pump mechanism, power source, and control systems for programming and regulating insulin delivery. The infusion cannula is inserted subcutaneously using a detachable needle, enabling continuous insulin administration [16].

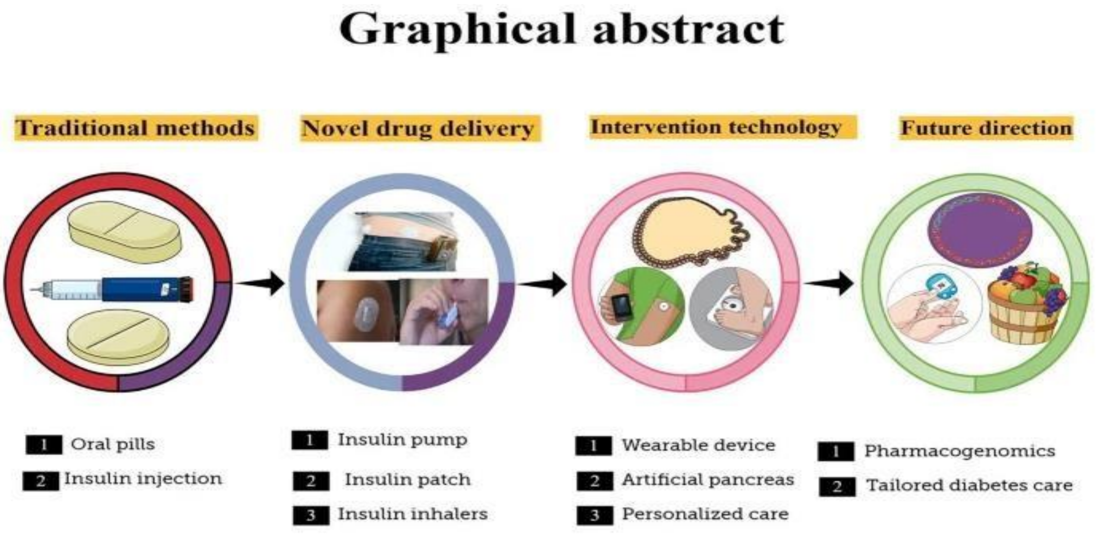


Figure 2: Graphical representation of traditional, novel, and future insulin delivery methods

6. Implantable Insulin Pumps

6.1 Insulin Pumps

Insulin pumps are medical devices designed to continuously deliver insulin from a reservoir to patients with diabetes, thereby helping to maintain stable blood glucose levels.

There are three main types of insulin pumps:

1. Traditional insulin pumps
2. Insulin patch pumps
3. Implantable insulin pumps (as shown in Figure 4) [17].

6.2 Traditional Insulin Pumps

Traditional insulin pumps consist of a wearable main unit, tubing, and an infusion cannula (Figure 3a). The main unit contains an insulin reservoir, pump mechanism, power source, and control systems for programming and regulating insulin delivery. The infusion cannula is inserted subcutaneously using a detachable needle, allowing continuous insulin administration [18].

6.3 Insulin Patch Pumps

Insulin patch pumps resemble traditional pumps but are more compact and smaller in size. They attach directly to the skin and feature a built-in infusion cannula (Figure 3b). These pumps can be either disposable or refillable and are capable of delivering insulin at both fixed and adjustable rates. Often, they are wirelessly controlled via an external device, enhancing convenience and patient comfort [19].

7. Implantable Insulin Pumps

Implantable insulin pumps are surgically inserted into the body, usually in the lower abdomen. These devices administer insulin intraperitoneally through a catheter (Figure 4). Compared to subcutaneous delivery, intraperitoneal administration allows for more efficient insulin absorption through the portal circulation, closely resembling natural insulin physiology . Implantable insulin pumps facilitate quicker insulin absorption and offer long term, stable glucose control compared to traditional delivery methods . These systems deliver insulin intraperitoneally, enabling more physiological uptake via the portal circulation. Currently, the only available model of implantable insulin pump is the Medtronic MIP 2007D. Once implanted under general anesthesia, the device's internal battery can last approximately 7–10 years [20]. However, the insulin reservoir (around 15 mL) needs to be refilled transcutaneous every three months, depending on patient usage. Image fig 3 Trends and technologies for implantable drug delivery systems Additionally, regular maintenance procedures, such as rinsing the pump and catheter, are recommended every 6–9 months to prevent insulin aggregation and catheter blockage . Despite their benefits, the use of implantable insulin pumps is limited due to factors such as their invasive nature, high cost (approximately €10,910 per year compared to €4,810 per year for traditional insulin pumps), and decreased clinical demand due to advancements in subcutaneous insulin formulations . In fact, Medtronic announced a recall of unused pumps in April 2020, effectively discontinuing this model . However, there is renewed research interest in developing next-generation implantable insulin pumps with smaller sizes, enhanced features, and integration with implantable glucose sensors to create fully automated closed-loop systems. Recently, transdermal insulin administration using microneedles has emerged as a promising method for diabetes management due to its minimally invasive, painless, and self-administered nature. These advantages significantly enhance patient compliance, which remains a major challenge in effective diabetes treatment [21].

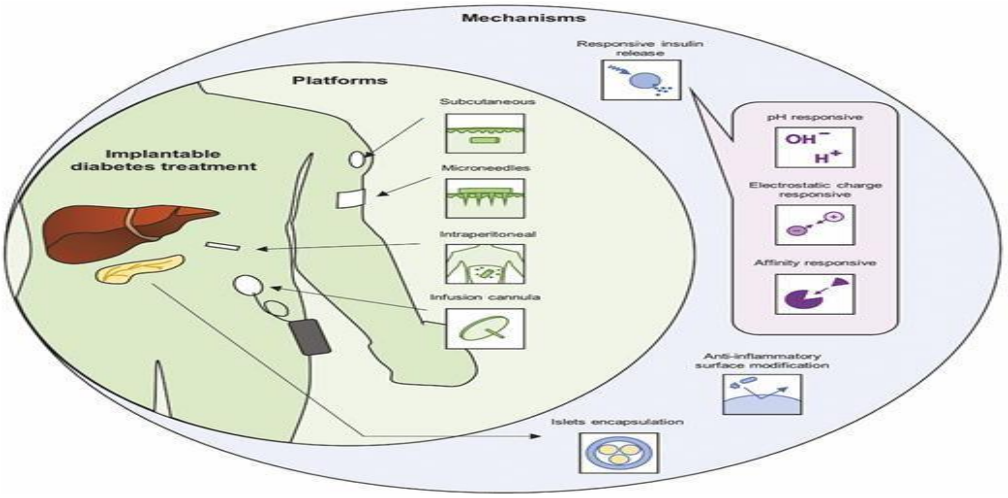
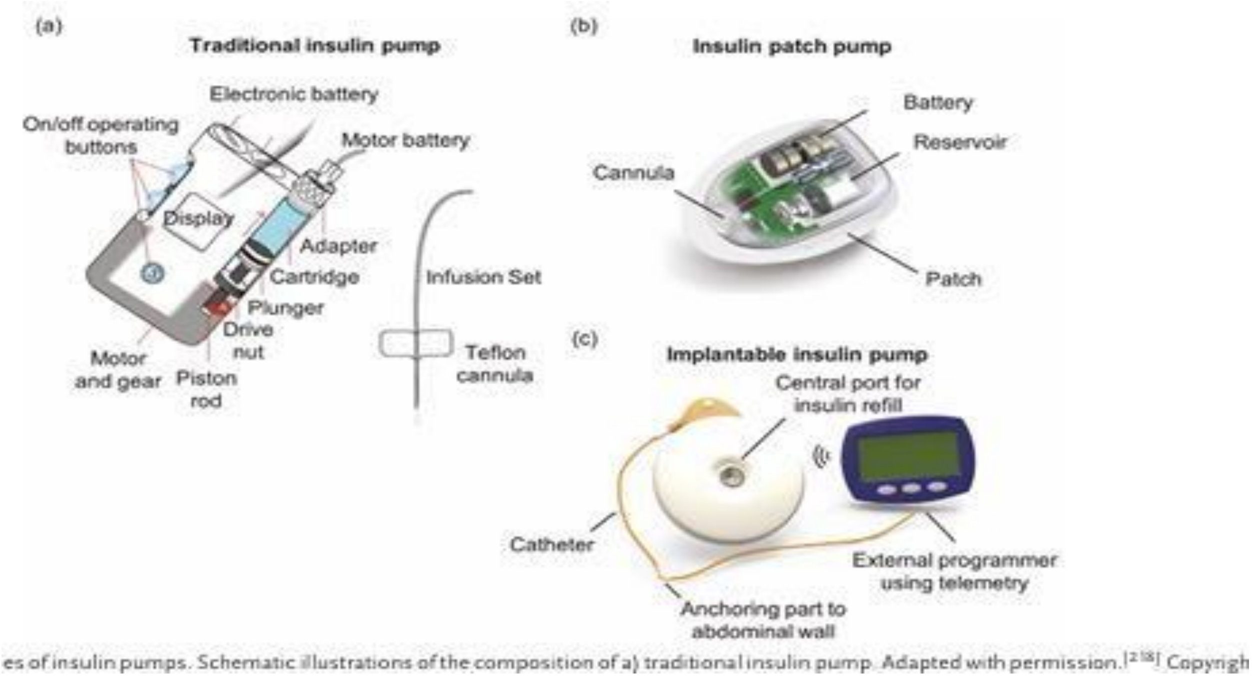


Figure 3: Trends and technologies for implantable drug delivery systems



es of insulin pumps. Schematic illustrations of the composition of a) traditional insulin pump. Adapted with permission.[218] Copyrigh

Figure 4: (a) Traditional insulin pump (b) Insulin patch pump (c) Implantable insulin pump

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9. Microneedles

Recent advancements in the use of microneedles for transdermal insulin delivery have garnered considerable attention in the research community, primarily due to their potential for self-administration, minimal invasiveness, and painless application. These attributes may significantly improve patient adherence, which remains a critical challenge in effective diabetes management. Researchers have explored the integration of various stimuli-responsive features into microneedle materials to enhance insulin release efficiency. In a study conducted by Chen et al., microneedles composed of a boronated, PBA-based hydrogel demonstrated responsiveness to glucose under normoglycemic conditions and typical physiological states[22]. This formulation also exhibited a stable release profile, unaffected by temperature variations (28–39 °C), thereby addressing concerns related to fluctuating skin temperatures in patients. In addition to traditional manufacturing techniques such as micro moulding, laser cutting, lithography, and etching, 3D printing has been employed to fabricate microneedles[23]. In the study conducted by Wu et al., microneedles were fabricated through the 3D printing of insulin-loaded bio ink, followed by post-stretching and cross-linking to form needle-like tips. The bio ink comprised alginate, hydroxyapatite, PBA, and insulin. These microneedles swell in solution, creating a porous structure that facilitates glucose diffusion and interaction with PBA for responsive insulin release[24]. In their in vivo experiments, the microneedles maintained normoglycemia in diabetic mice for up to 40 hours. In contrast, control microneedles lacking PBA resulted in a burst release of insulin, leading to hypoglycaemia after 3 hours. Over a 4-day observation period, mice treated with microneedles demonstrated effective insulin release. addition to conventional fabrication techniques such as micro moulding, laser cutting, lithography, and etching, a 3D printing method was employed for the production of microneedles[25]. The bio ink composition included alginate, hydroxyapatite, PBA, and insulin. When immersed in a solution, microneedles expand, creating a porous structure that permits glucose to enter and interact with PBA, facilitating a responsive release. In contrast, microneedles without PBA caused a rapid release of insulin, leading to hypoglycaemia after 3 hours. Over a 4-day period, mice treated with these microneedles drank less water, urinated less, experienced less weight loss, and had lower glycated albumin levels, all of which indicate effective diabetes management[26]. Additionally, microneedles can be integrated with a glucose monitoring system to create a These systems can be integrated into closed-loop diabetic management systems, as demonstrated by Lee et al. a wearable patch combined with a multi-mode sweat sensor (glucose, pH, humidity, and temperature) and temperature-triggered delivery of a non-insulin hypoglycaemic drug (metformin)) was presented [27].

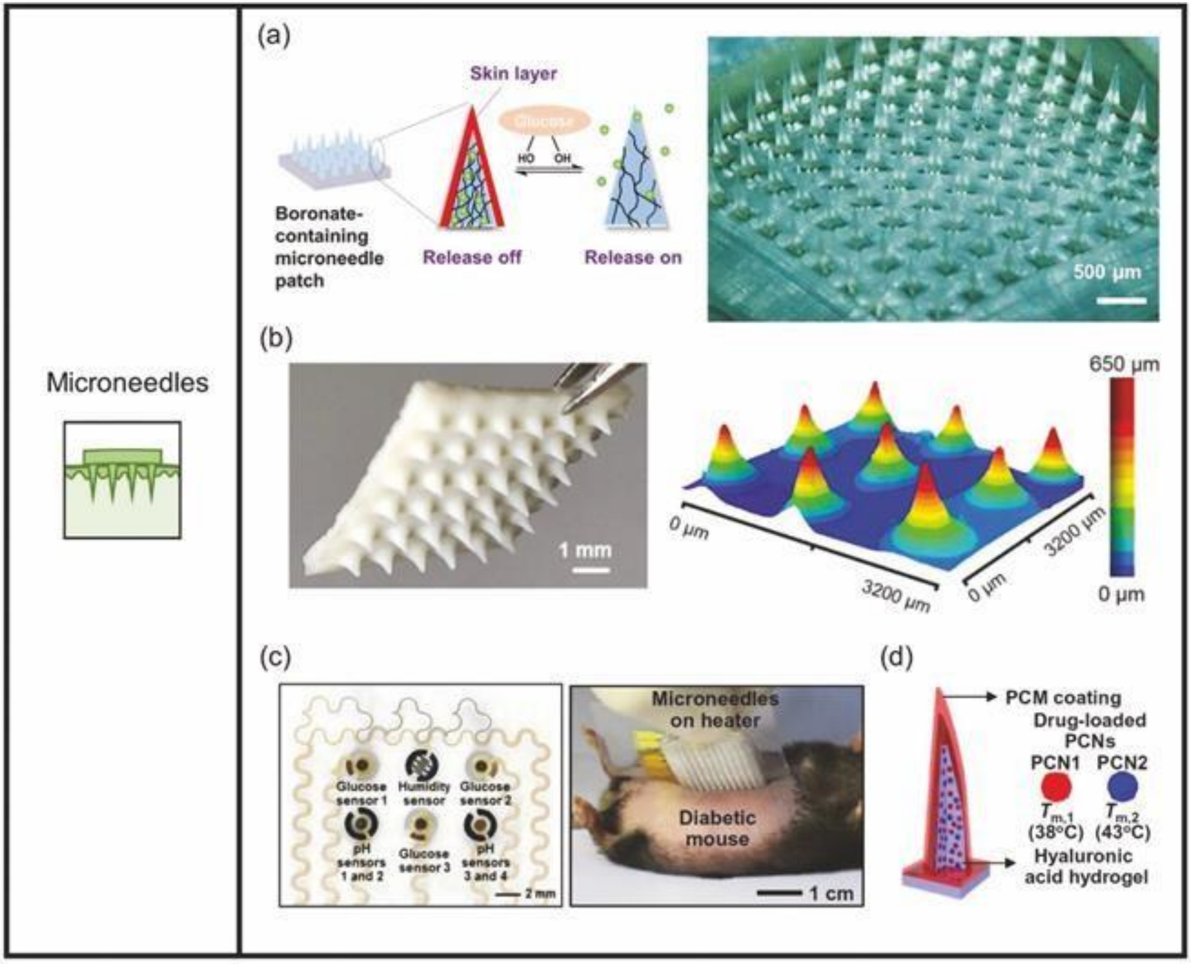

Figure 5: Microneedle-based transdermal insulin delivery systems.

Microneedles made of biocompatible hyaluronic acid hydro gel were coated with drug-loaded phase change nanoparticles (PCNs). Two PCNs made with either palm oil (melting tempera true Tm = 38 °C) or tridecanoic acid (Tm = 43 °C) remained stable and intact even after microneedles have penetrated the skin. When hyperglycemia was detected (GOx based electrochemical sensing with pH, humidity, and temperature compensation), in targeted heaters triggered the release of the drugs. Six different drug release profiles were achieved by using three heating elements and two temperature points (40 and 45 °C). In their in vivo tests, the blood glucose level of diabetic mice was lowered in a controllable fashion (from > 22 mm to 7.6 mm, with < 11 being normoglycemic state) within 6 h[28].

10. Islet Encapsulation

Islet implantation presents an effective approach to rejuvenate pancreatic function through a bioengineered bio-similar remedy. In the host body, β-cell islets respond to varying glucose concentrations and release insulin, creating a natural biological closed-loop system. Nonetheless, when employing islet implantation for diabetes treatment, the encapsulation of islets is crucial for the survival and correct function of the β-cells[29]. In addition to the demands for strong physical and mechanical designs to enable easy implantation, monitoring, and potential retrieval, the encapsulation must exhibit outstanding biocompatibility for enduring safety profiles and selective permeation. The encapsulation must establish and uphold a localized environment that facilitates the transfer of nutrients, metabolic substances, and waste while excluding immune mediating cells (i.e., complement, immunoglobulins, cytokines) These immuno-isolation or immune stealth characteristics can free patients with islet implants from the difficulties of enduring immune suppression treatments or worries about potential rejection or failure.[30]In microencapsulation, a single or small group of β-cells or islets is encased in a microscale capsule. These methods enhance the surface area-to-volume ratio to facilitate molecular exchange, potentially reducing immediate islet loss from inadequate oxygen supply and blood vessel formation soon after implantation None the less, because of the significant quantity of islets required for each implantation (10000 per kilogram of body weight), maintaining capsule uniformity is challenging. In microencapsulation, numerous islets are contained in a single, larger capsule, facilitating better adjustment and monitoring of each capsule. Nonetheless, this method experiences inadequate nutrient distribution. In the study conducted by An et al., the Thread Reinforced Alginate Fiber for Islets encapsulation (TRAF FIC) device was developed by merging alginate hydrogel with nylon thread (Figure 11a).

folded, were initially coated with poly(methyl methacrylate)/N, N-dimethylformamide/calcium chloride (PMMA/DMF/CaCl2), followed by alginate hydrogel through in situ cross-linking The TRAFFIC devices exhibited outstanding biocompatibility, evidenced by the absence of fibrosis following 7 months of intraperitoneal implantation in mice (Figure 11b). In vivo tests involved encapsulating human or mouse islets and implanting them into diabetic rats, resulting in sustained normoglycemia over 14 months .In contrast, unencapsulated islets did lower glucose levels temporarily but faced rejection after 2 weeks.

The study by Bose et al. introduced an implant capable of encapsulating different therapeutic xenogeneic cells [32]. It was made of silicone elastomer featuring microchannels for cell storage, along with a polycarbonate track-etched membrane that has specific pore sizes (< 0.8 µm) to prevent immune cell infiltration and rejection of the implant When surrounded by rat pancreatic islets ,such a device maintained normal blood sugar levels in diabetic mice for more than 75 days. In the study conducted by Liu et al., a macro-porous design featuring a secondary core-shell configuration was fabricated using a 3D coaxial printing technique (Figure 11d).[203] The alginate/gelatin meth acryloyl bio ink demonstrated excellent stability, printability, and biocompatibility for the survival of islets[33]. The 3macroporous design guaranteed minimal spacing between every islet and adjacent tissues, allowing for sufficient diffusion of nutrients and oxygen. Islets in the core were additionally surrounded by supporting cells in the shell. The in vivo experiments demonstrated strong implant integrity in mice after 21 days, with noticeable vascularization observed after 14 days. Nonetheless, in vitro evaluations of insulin release indicated that encapsulated islets were impaired after 3 days in the culture medium, likely due to disrupted glucose diffusion or hypoxic conditions[34].

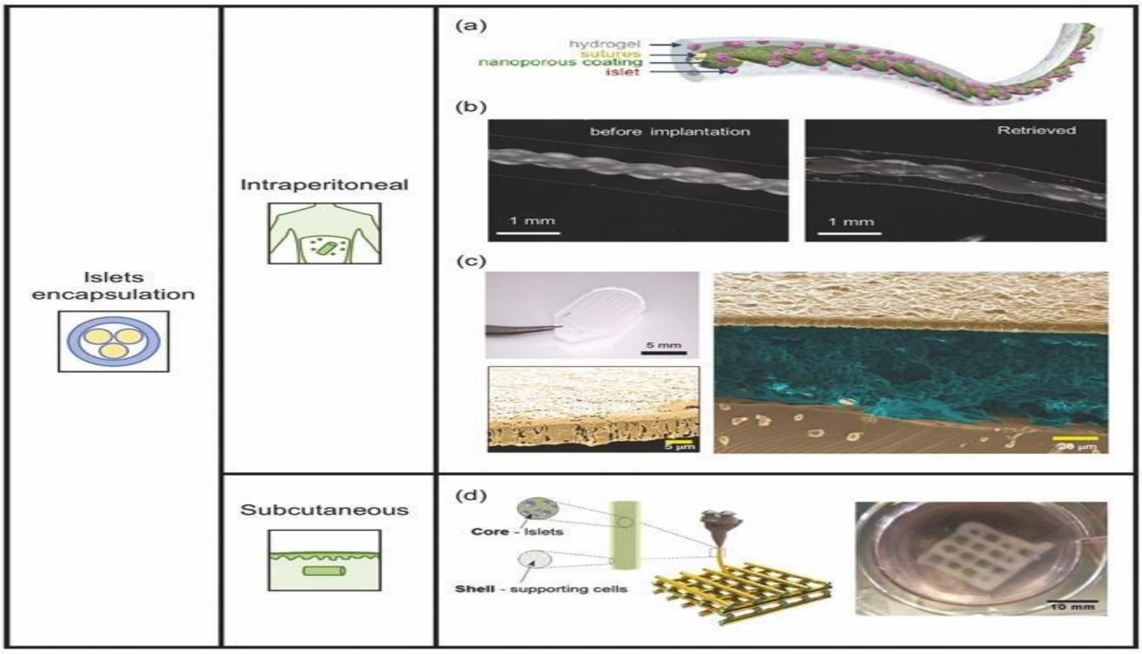

Figure 6: Islet encapsulation for β-cell implantation. (a) Schematic illustration of the TRAFFIC device. (b) Microscopic images of the device before (left) and after (right) 7 months of implantation. (c) Retrievable macroscopic encapsulation device for long-term implantation. (d) Coaxially 3D-printed islet microencapsulation implant.

11. Wearable Devices for Immediate Glucose Tracking

Recent years have seen substantial advancements in direct glucose monitoring technologies, making wearable devices crucial components in contemporary diabetes management [35]. These technologies include conventional continuous glucose monitoring (CGM) systems as well as cutting-edge non-invasive options like smartwatches and sweat-detecting sensors [36]. Continuous Glucose Tracking (CGT) CGM systems continue to be the benchmark for real-time glucose tracking. These devices utilize minimally invasive sensors placed under the skin to continuously monitor glucose levels in interstitial fluid (Figure 3a). They offer real-time information, allowing users to track trends and anticipate glucose changes. Clinical research indicates that CGM systems enhance glycemic management and decrease occurrences of both hypoglycemia and hyperglycemia [37].

12. Glucose Monitoring Using Smartwatches

The incorporation of glucose tracking smartwatches signifies a significant progress in noninvasive methods (Figure 3b). In contrast to CGM systems, these devices utilize optical or bioimpedance sensors to evaluate glucose levels without breaking the skin [38].They examine physiological metrics like heart rate variability, blood circulation, and skin characteristics to deduce glucose levels .Despite their potential, these technologies remain in development, with continuous research aimed at enhancing accuracy and dependability [39].

13. Glucose Monitoring Through Sweat

Newly developed wearable technologies encompass glucose monitoring systems that utilize sweat [40]. Stretchable sweat sensors leverage the relationship between sweat and blood glucose levels to offer a non-invasive monitoring method. These systems utilize cutting-edge materials and microfluidics to develop flexible, comfortable devices ideal for long-term use .Current research is aimed at improving sensitivity, precision, and long-term reliability while ensuring user comfort and the durability of the device [41].

14. Artificial Intelligence (AI) has emerged as a revolutionary resource in diabetes care, facilitating sophisticated glucose forecasting and tailored treatment approaches.

The combination of wearable technology and AI powered algorithms establishes a robust platform that offers immediate insights, optimizes glycemic regulation, and improves overall management of disease outcomes [42]. AI technologies, such as machine learning (ML) and deep learning algorithms, can efficiently forecast glucose variations by utilizing various physiological inputs. These systems evaluate past glucose information, meal schedules, physical exercise, and additional contextual elements to predict glycemic patterns . These predictive abilities allow for preemptive actions, such as adjusting insulin doses and changing dietary plans, thus lowering the chances of hypoglycemia and hyperglycemia [43].Wearable gadgets produce substantial amounts of data, such as glucose levels, heart rate, exercise activities, sleep patterns, and medication records. When combined with AI systems, this data is transformed into significant and practical insights .For instance, continuous glucose monitoring (CGM) information paired with AI algorithms can detect patterns and give early alerts of glucose imbalances, enabling prompt behavioral or treatment modifications [44].

15. Main Advantages of AI Integration

- Immediate feedback: AI algorithms evaluate wearable data and deliver prompt insights on glucose patterns, recommending essential behavioral or therapeutic adjustments .
- Predictive analytics: AI technologies anticipate future
- glucose fluctuations, aiding in the prevention of harmful glycemic incidents.
- AI-driven decision assistance: AI-powered systems suggest insulin dosing, dietary changes, and modifications in activity, thus alleviating patient burden and enhancing treatment precision [45].
- In general, merging wearable technology with AI signifies a fundamental change in diabetes management. Utilizing real-time tracking and predictive analytics, these systems provide more accurate, tailored, and effective disease management options[46].

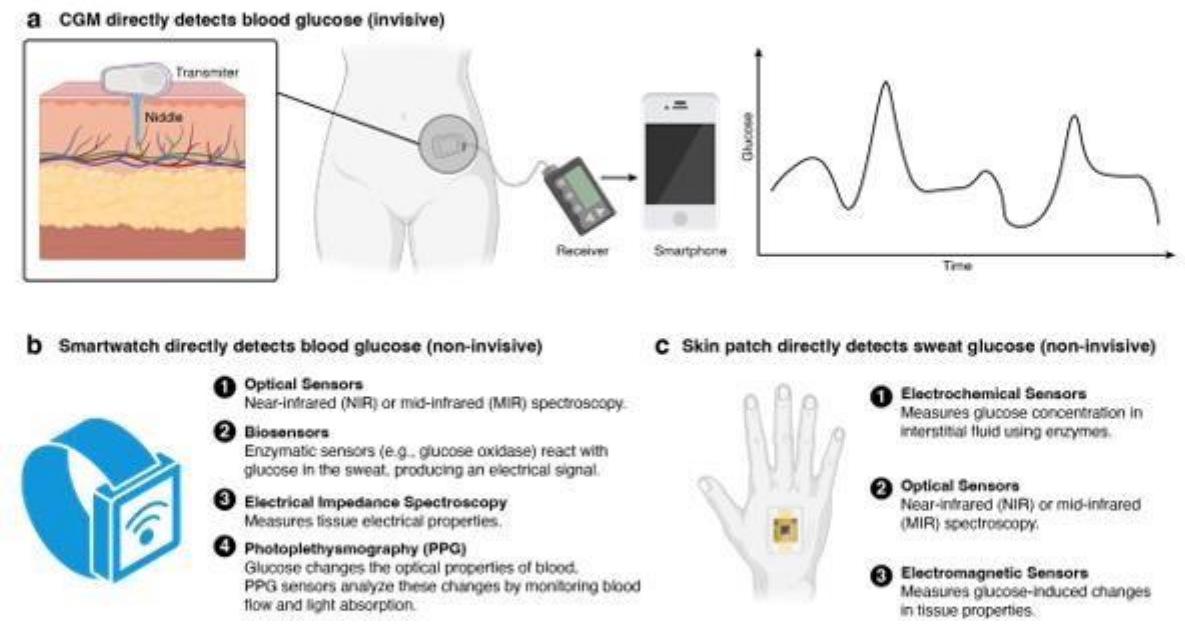

Figure 7:Wearable glucose monitoring technologies

16. Devices Utilizing Microchips

Drug delivery systems utilizing microchips offer a novel method for regulated insulin delivery. These devices employ implantable microchips that can store and release insulin based on real-time glucose levels. The microchip is generally placed under the skin and set up to deliver insulin in a regulated and adaptive way. Certain systems can be controlled remotely via devices or smartphone apps, enabling tailored therapy modifications. This technology minimizes the necessity for regular injections and offers a more convenient and patient-cent red treatment alternative . Microchip-driven systems provide numerous benefits, such as accurate dosing, programmability, and possible connection with glucose monitoring systems for closed-loop regulation. As research advances, these devices could be significant in the future of intelligent and automated diabetes care[47].

17. CONCLUSION:

The advancements in implantable insulin delivery systems and wearable glucose monitoring technologies represent a transformative shift in diabetes management. These innovations offer enhanced precision, real-time monitoring, and improved patient compliance, addressing many limitations of traditional approaches. Implantable devices provide sustained and controlled insulin release, reducing the burden of frequent injections, while wearable sensors enable continuous glucose tracking with increasing accuracy and user convenience. Together, these technologies pave the way for more personalized and effective diabetes care, minimizing complications and improving quality of life. Future developments focusing on integration, miniaturization, biocompatibility, and data analytics will further optimize these systems, fostering seamless closed-loop solutions. Continued interdisciplinary research and clinical validation are essential to translate these promising advances into widespread clinical practice, ultimately advancing toward fully autonomous and patient-centric diabetes management

18. . REFERENCES:

[1] Lu X, Xie Q, Pan X, Zhang R, Zhang X, Peng G, Tong N. Type 2 diabetes mellitus in adults: pathogenesis, prevention and therapy. Signal Transduct Target Ther. 2024;9(1):262.
[2] DeFronzo R, Ferrannini E, Groop L, et al. Type 2 diabetes mellitus. Nat Rev Dis Primers. 2015;1:15019.
[3] Kolb H, Martin S. Environmental/lifestyle factors in the pathogenesis and prevention of type 2 diabetes. BMC Med. 2017;15(1):131.
[4] American Diabetes Association. Diagnosis and classification of diabetes mellitus. Diabetes Care. 2010;33(Suppl 1):S62–S69.
[5] Zhang J, Xu J, Lim J, Nolan JK, Lee H, Lee CH. Wearable glucose monitoring and implantable drug delivery systems for diabetes management. Adv Healthcare Mater. 2021;10:2100194.
[6] Samuel VT, Shulman GI. The pathogenesis of insulin resistance: integrating signaling pathways and substrate flux. J Clin Invest. 2016;126(1):12–22.

[7] Katsarou A, Gudbjörnsdottir S, Rawshani A, et al. Type 1 diabetes mellitus. Nat Rev Dis Primers. 2017;3:17016.

[8] van der Heide LP, Ramakers GM, Smidt MP. Insulin signaling in the central nervous system: learning to survive. Prog Neurobiol. 2006;79(4):205–221.

[9] Arnold SE, Arvanitakis Z, Macauley-Rambach SL, Koenig AM, Wang HY, Ahima RS, Nathan DM, et al. Brain insulin resistance in type 2 diabetes and Alzheimer disease: concepts and conundrums. Nat Rev Neurol. 2018;14(3):168–181.

[10] Liu D, Yang F, Xiong F, Gu N. The smart drug delivery system and its clinical potential. Theranostics. 2016;6(9):1306–1323.

[11] Magill E, Demartis S, Gavini E, Permana AD, Thakur RRS, Adrianto MF, Larrañeta E, et al. Solid implantable devices for sustained drug delivery. Adv Drug Deliv Rev. 2023;199:114950.

[12] Quarterman JC, Geary SM, Salem AK. Evolution of drug-eluting biomedical implants for sustained drug delivery. Eur J Pharm Biopharm. 2021;159:21–35.

[13] Xie J, Zhang T, Jiang J, Xue W, Wang W, Ni J, Liu X, et al. Advances in magnesium-based implants for biomedical applications: a comprehensive review and future perspectives. J Magnesium Alloys. 2025.

[14] Saadat E. Pharmaceutical implants: from concept to commercialization. In: Advances in Drug Delivery Systems for Healthcare: From Concept to Clinic. Bristol, UK: IOP Publishing; 2024. p.1–1.

[15] Murtaza G, Riaz S, Zafar M, Ahsan Raza M, Kaleem I, Imran H, Bashir S, et al. Examining the growing challenge: prevalence of diabetes in young adults. Med Int. 2024;5(1):2.

[16] Rimon MTI, Hasan MW, Hassan MF, Cesmeci S. Advancements in insulin pumps: a comprehensive exploration of insulin pump systems, technologies, and future directions. Pharmaceutics. 2024;16(7):944.

[17] Brown S, Romeo GR, Toschi E. Insulin pumps for individuals with type 2 diabetes. Diabetes Spectr. 2025;38(3):228–238.

[18] Kesavadev J, Krishnan G, Benny N. Insulin delivery: an evolution in the technology. In: The Diabetes Textbook: Clinical Principles, Patient Management and Public Health Issues. Cham: Springer International Publishing; 2023. p.1141–1158.

[19] Yang R, Yang Z, Chi J, Zhu Y. Insulin delivery devices in diabetes management: applications and advancements. Intell Pharm. 2025;3(3):235–242.

[20] Niloy KK, Lowe TL. Injectable systems for long-lasting insulin therapy. Adv Drug Deliv Rev. 2023;203:115121.

[21] Wang J, Liu Z, Jiao L, Zhou J, Wang T, Li C, Zhang L, et al. Efficacy and safety of needle-free injection in patients with type 2 diabetes mellitus undergoing intensive insulin therapy: a randomized controlled trial based on the flash glucose monitoring system. Front Endocrinol. 2025;16:1652388.

[22] Gattu K, Godugu D, Jain H, Jadhav K, Cho H, Rojekar S. Microneedle technologies for drug delivery: innovations, applications, and commercial challenges. Micromachines. 2026;17(1):102.

[23] Wei D, Yang W, Liu F, Song X. 3D printed microneedles with controlled release for drug delivery study in an ex-vivo model. Available at: SSRN 5263955.

[24] Pi M, Liu W, Huang B, Wu T, Zhang T, Wang W. Development of glucose/pH responsive smart hydrogel of carbopol and application in microneedles. J Polym Res. 2024;31(6):162.

[25] Mohite P, Patel M, Puri A, Pawar A, Singh S, Prajapati B. Revisiting the advancement with painless microneedles for the diagnosis and treatment of dermal infections: a review. Nanofabrication. 2023;8.

[26] Mohite P, Patel M, Puri A, Pawar A, Singh S, Prajapati B. Revisiting the advancement with painless microneedles for the diagnosis and treatment of dermal infections: a review. Nanofabrication. 2023;8.

[27] Lin R, Jiang Z, Chi Y, Xing L, Long Z, Xue X, Chen M. A flexible wireless skin patch for synchronized glucose monitoring and regulation. Microsyst Nanoeng. 2026;12(1):23.

[28] Xie L, Lu W, Zhang Y, Deng L, Liu M, Gao H, Wang G, et al. Glucose-activated switch regulating insulin analog secretion enables long-term precise glucose control in mice with type 1 diabetes. Diabetes. 2023;72(6):703–714.

[29] Opara A, Jost A, Dagogo-Jack S, Opara EC. Islet cell encapsulation: application in diabetes treatment. Exp Biol Med. 2021;246(24):2570–2578.

[30] Ho BX, Teo AKK, Ng NHJ. Innovations in bio-engineering and cell-based approaches to address immunological challenges in islet transplantation. Front Immunol. 2024;15:1375177.

[31] Emerson AE, Lyons Q, Becker MW, Sepulveda K, Hiremath SC, Brady SR, Weaver JD, et al. Hydrogel injection molded complex macroencapsulation device geometry improves long-term cell therapy viability and function in the rat omentum transplant site. Biomaterials. 2025;317:123040.

[32] Emerson AE, Lyons Q, Becker MW, Sepulveda K, Hiremath SC, Brady SR, Weaver JD, et al. Hydrogel injection molded complex macroencapsulation device geometry improves long-term cell therapy viability and function in the rat omentum transplant site. Biomaterials. 2025;317:123040.

[33] Sathisaran I. 3D printing and bioprinting in the

battle against diabetes and its chronic complications. Front Bioeng Biotechnol. 2024;12:1363483.

[34] Luo Z, Dong Y, Yu M, Fu X, Qiu Y, Sun X, Chu X. A novel insulin delivery system by β-cells encapsulated in microcapsules. Front Chem. 2023;10:1104979.

[35] Liu L, Zhan K, Kilpijärvi J, Kinnunen M, Zhao Y, Zhang Y, Huang J, et al. Portable and label-free optical detection of sweat glucose using functionalized plasmonic nanopillar array. Microsyst Nanoeng. 2026;12(1):43.

[36] Sedighi A, Kou T, Huang H, Li Y. Noninvasive on-skin biosensors for monitoring diabetes mellitus. Nano Micro Lett. 2026;18(1):16.

[37] Bailey TS, Liljenquist DR, Denham DS, Brazg RL, Ioacara S, Masciotti J, Kaufman FR, et al. Evaluation of accuracy and safety of the 365-day implantable eversense continuous glucose monitoring system: the enhance study. Diabetes Technol Ther. 2025;27(5):407–411.

[38] Nguyen ATP, Huynh TV, Huynh HN, Tran TH, Phan MH, Thi HVN, Tran TN, et al. The open-source multi-wavelength non-invasive blood glucose sensing system. Sci Rep. 2025.

[39] Khamesian S, Arefeen A, Grando MA, Thompson BM, Ghasemzadeh H. Type 1 diabetes management using glimmer: glucose level indicator model with modified error rate. arXiv. 2025;arXiv:2502.14183.

[40] Liu G, Dou X, Zhang P, Yin S, Tan Q, Jin X, Zhang X, et al. Development of a wearable microfluidic amperometric sensor based on spatial three-electrode system for sweat glucose analysis. Talanta. 2025;293:128101.

[41] Chen X, Wang C, Wei W, Liu Y, Ge SS, Zhou L, Kong H. Flexible and sensitive pressure sensor with enhanced breathability for advanced wearable health monitoring. npj Flex Electron. 2025;9(1):101.

[42] Metwally AA, Heydari AA, McDuff D, Solot A, Esmaeilpour Z, Faranesh AZ, Prieto JL, et al. Insulin resistance prediction from wearables and routine blood biomarkers. Nature. 2026;1–11.

[43] Brügger V, Kowatsch T, Jovanova M. Predicting postprandial glucose excursions to personalize dietary interventions for type-2 diabetes management. Sci Rep. 2025;15(1):25920.

[44] Luo J, Kumbara A, Shomali M, Han R, Iyer A, Aleppo G, Gao G, et al. A large sensor foundation model pretrained on continuous glucose monitor data for diabetes management. npj Health Syst. 2025;2(1):35.