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Nano-Therapeutics in Diabetes Mellitus: Revolutionizing Diagnosis, Treatment, and Drug Delivery

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Abstract

Diabetes mellitus is a chronic metabolic disorder in which blood glucose concentration remains high over an extended duration, resulting in significant lethal complications, including neuropathy, nephropathy and cardiovascular diseases. However, conventional diabetes management strategies, including insulin therapy and oral hypoglycemic agents, rarely exhibit poor bioavailability, high doses, off target delivery, etc. Nanotechnology has brought the rise of diabetes treatment revolution, by overcoming the challenges present in standard treatment, owing to the emergence of nanotechnology, which has allowed precise drug delivery, real time glucose monitoring and regenerative therapy. In this review, nanotechnology roles in diabetes are discussed with regards to two of its three dimensions; specifically, the existing nano-based therapeutics, drug delivery systems and biosensing technologies in the management of diabetic condition. The recent advances in the polymeric nanoparticles, liposomes, micelles, hydrogels and metallic nanoparticles have greatly enhanced insulin delivery, non-insulin drug delivery, and glucose monitoring. Furthermore, artificial intelligence hybridized nanomedicine is personalized diabetes management by improving treatment strategies and predictive analytics. To thoroughly review recent trends in nano-therapeutics for diabetes, extensive literature review on Scopus and SCI indexed journals was performed for the identification of certain parameters, like bioavailability, drug release kinetics, biocompatibility and therapeutic efficacy. Controlled and targeted drug delivery is one of the powerful features utilized by nanotechnology to better treat diabetes. Improved insulin stability and prolonged systemic circulation of polymeric nanoparticles and lipid based nanocarriers, real time glucose monitoring using glucose responsive nanocarriers and biosensors have reduced risks of hypo and hyperglycemia. With respect to the application of regenerative nanomedicine, such as stem cell loaded nanoparticles and gene therapy, regenerative nanomedicine has emerged as a new direction for pancreatic beta cell regeneration and as a potential curative treatment for diabetes. However, there are many challenges to patient use, such as large-scale manufacture, regulatory approvals and long-term safety issues that need to be overcome before clinical translation. The future research should concentrate on designing hybrid nanoplatforms, biodegradable nanocarriers and AI integrated nano diagnostics to improve personalized diabetes care.

Keywords: Diabetes Mellitus, Nanotechnology, Nano-Therapeutics, Insulin Nanocarriers, Biosensors, Personalized Medicine, Artificial Intelligence

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INTRODUCTION

Diabetes mellitus is a chronic metabolic disorder characterized by a defect in the insulin secretion, insulin action, or both because of which there is a persistent hyperglycemia [1]. People an upward trend in its prevalence, it has emerged as a major global health challenge since more than 537 million people are affected by it worldwide and the figure is predicted to increase up to 643 million in 2030 [2]. The disease is usually divided into type 1diabetes, where it is due to autoimmune destruction of pancreatic beta cells and the subsequent insulin deficiency, and type 2 diabetes, which is a result of insulin resistance and progression to pancreatic beta cell dysfunction [3]. However, despite the improvement in treatment and management strategies, diabetes continues to be one of the leading causes of morbidity and mortality due to its related complications in the form of cardiovascular diseases, neuropathy, nephropathy & retinopathy. Subcutaneous injections of insulin and oral antidiabetic medications used for conventional treatment have numerous difficulties [4]. However, frequent injections of insulin results in poor patient compliance, and many painful injections and the risk of hypoglycemia [5]. There are problems with bioavailability associated with oral hypoglycemic drugs, such as the metformin and sulfonylureas, which are degraded in the gastrointestinal/liver systems due to enzymatic degradation and hepatic first-pass metabolism and sustained low absorption [6]. Conventional ways of monitoring glucose, such as finger prick blood glucose testing, are invasive and lead to intermittently monitoring of the glucose level, never tracking it in real time. To remedy these drawbacks there is a need for more efficient, patient friendly and noninvasive alternatives for diabetes diagnosis, treatment and drug deliver; Nanotechnology, can however bring promising innovations in the diabetes management by enhancing drug delivery, improving glucose monitoring and enable regenerative therapies [7]. Polymeric nanoparticles, liposomes, micelles, hydrogels, and metallic nanoparticles have shown significant potential in increasing bioavailability of drugs, decrease side effects, and delivery of the drug in controlled manner [8]. Non-invasive glucose monitoring through saliva, sweat and tear fluid is allowed by nano-based biosensors. Moreover, regenerative nanomedicine strategies involving nanoparticle assisted stem cell therapy and gene delivery technologies will enable the regeneration of pancreatic beta cells for the treatment of diabetes, leading to diabetes remission for long term [9]. This review highlights the emerging nano therapeutics for diabetes regarding futuristic drug delivery systems, state of the art in glucose monitoring and regenerative options. The attention will also be directed to investigate regulatory hurdles, commercialization hindrances, as well as prospects of using nanotechnology coupled with artificial intelligence and precision medicine in the field of personalized diabetes management [10].

FUNDAMENTALS OF NANO-THERAPEUTICS FOR DIABETES

Nanotechnology in Medicine: Basic Concepts

Nanotechnology refers to the field of research at nanoscale (typically, 1 to 100 nm) to develop material and its systems having improved physicochemical properties [11]. Nanotechnology has sparked revolutionary progress in diagnostics, drug delivery, and regenerative medicine in medicine by increasing bioavailability, lowering toxicity and affecting targeted drug delivery at the molecular and cellular level [12]. The power of manipulation being able to operate at the molecular level opens new possibilities of sophisticated drug carriers that can cross biological barriers, regulate drug release and promote targeting action of drugs; for instance, to improve outcome of treatment in chronic diseases like diabetes mellitus [13].

Types of Nanomaterials Used in Diabetes

The administration of diabetes care through nanomaterials delivers three essential benefits including controlled drug delivery along with improved glucose detection methods and enhanced pancreatic tissue healing abilities [14]. Nanocarriers serving diabetic therapy exist in the forms of polymeric nanoparticles and liposomes and micelles and hydrogels and metallic nanoparticles [15]. The drug delivery benefits of polylactic-co-glycolic acid (PLGA) and chitosan-based systems include both extended insulin release and prevention of enzymatic damage to the insulin drug [16]. The drug absorption rates improve through liposomes and micelles treatment alongside their ability to boost drug solubility and bioavailability combined with hydrogels capacity for glucose-sensitive insulin delivery [17]. Gold and silver metallic nanoparticles have exceptional optical properties together with electrical characteristics that enhance both glucose sensing and targeted drug delivery systems [18]. Nanomaterials possess specific benefits and drawbacks that are listed in Table 1.

Mechanisms of Nanoparticle-Based Drug Delivery and Biosensing

In diabetes management, nanocarrier efficiency is because of their uniqueness in drug delivery of passive, active and stimuli responsive release [19]. Nanoparticles that accumulate in certain tissues are passive targeted through enhanced permeability and retention effect. Surface modifications with ligands, antibodies, or peptides also can make the therapeutic active targeting [20]. To solve the problem of unregulated, free insulin release, smart insulin delivery systems have been developed, which employ stimuli responsive nanoparticles that release drugs upon receipt of external triggers, such as pH, temperature or glucose concentration [21]. Nanomaterials are utilized in glucose biosensing to provide high specificity and sensitivity, as they provide large surface area for enzyme immobilization and facilitate rapid electron transfer during real time monitoring of glucose with high accuracy [22]. There are significant improvements in patient compliance, treatment efficacy, if not real time monitoring of glucose for nanotechnology-based drug delivery and biosensing strategies. Together, nanocarriers and various sensing technologies give integrated strategies for diabetes management, as further presented in the following sections [23].

Table 1. Classification and applications of nanomaterials in diabetes management.

Nanomaterial Type	**Key Properties**	**Applications in Diabetes**	**References**
Polymeric nanoparticles	Biodegradable, sustained release	Oral insulin delivery, gene therapy	[24]
Liposomes	High biocompatibility, drug encapsulation	Insulin and GLP-1 analog delivery	[25]
Micelles	Amphiphilic, enhances solubility	Hydrophobic drug solubilization	[26]
Hydrogels	High water retention, glucose-sensitive	Smart insulin delivery systems	[27]
Metallic nanoparticles	Optical, electrical properties	Glucose biosensors, targeted drug delivery	[28]

Advancements in Nano-Therapeutics for Diabetes

The integration of artificial intelligence, nanotechnology, along with real time monitoring system is shaping the future of the treatment of diabetes [29]. Future diabetes care has moved to a paradigm where the development of multifunctional nanoplatforms that can simultaneously deliver drugs, biosense, and embolize trauma in one step is underway. Because of this, researchers are now exploring hybrid nanostructures, like polymer metal composites and lipid polymer hybrid nanoparticles, to improve drug stability and improve therapeutic outcome [30]. Nanotechnology has great potential as an object for personalized diabetes treatment and its possibility is in personalized therapy based on patient's own glucose fluctuations and metabolic profiles [31].

Nanotechnology in Diabetes Diagnosis and Monitoring

Diabetes diagnosis and monitoring using nanotechnology has been made possible due to the ability to find multiple precise, real time, and noninvasive glucose detection methods [32]. However, conventional glucose monitoring techniques, for example, blood glucose meters are time consuming invasive approach which cause pain, discomfort, and poor patient compliance [33]. Integration of nanotechnology in biosensors and point of care diagnostic systems has greatly improved sensitivity, specificity and enhanced rapid detection of glucose level [34]. Biosensors are based on nanomaterials, such as carbon nanotubes, quantum dots, gold nanoparticles, graphene, etc. for improved electrochemical and optical glucose sensing [35]. In addition, wearable nanotechnology presents the form of smart patches and implantable sensors that enable minimal invasiveness at continuous glucose monitoring. Regarding diabetes diagnostics, the use of AI powered lab on a chip system also gives rise to rapid & real time blood glucose analysis and thus enables personalized disease management [36]. Because of these advancements in nano diagnostics, glucose detection techniques that do not require use of bodily fluids, like saliva, sweat, and tears, have been developed that will improve compliance of the patients [37]. In Table 2, nano based diagnostic technologies are described along with their usage for monitoring diabetes.

Table 2. Nano-based diagnostic technologies for diabetes monitoring.

Nano-Diagnostic Technique	Nanomaterial Used	Detection Method	Advantages	Clinical Application	Reference
Electrochemical Glucose Biosensors	Carbon nanotubes, gold nanoparticles, Graphene	Enzymatic & non-enzymatic glucose oxidation	High sensitivity, fast response	Blood glucose monitoring	[38]
Optical Biosensors	Quantum dots, silver nanoparticles	Fluorescence-based glucose sensing	Non-invasive, multiplex detection	Tear, saliva glucose monitoring	[39]
Wearable Nano-Sensors	Smart patches, Hydrogel-based nanosensors	Continuous glucose sensing via skin interstitial fluid	Minimally invasive, real-time monitoring	Continuous glucose monitoring devices	[40]
Lab-on-a-Chip Technology	Nanostructured microfluidic devices	AI-integrated glucose assays	Rapid, real-time blood glucose analysis	Point-of-care diagnostics	[41]
Implantable Nano-Sensors	Gold nanowires, Graphene-based sensors	Long-term in vivo glucose detection	Continuous monitoring, minimal patient intervention	Subcutaneous glucose monitoring implants	[42]

Nano-Based Biosensors for Glucose Monitoring

The nano-based biosensors are highly sensitive, rapid, and non-invasive glucose detectors. The biosensors are based on nanomaterials, like carbon nanotubes, gold nanoparticles and graphene, for better electron transfer, and more glucose sensing ability [43]. Glucose biosensors are also enzymatic and depend on glucose oxidase to oxidize the glucose, resulting in an electrochemical signal that is proportional to glucose concentration [44]. Despite the inability of enzymatic degradation, non-enzymatic glucose biosensors consisting of nanocomposites, such as platinum and gold nanoparticles provide higher stability and long-term performance to overcome the limitation of enzymatic degradation. Real time glucose monitoring through smart wearable biosensors has also drawn attention as a means of continuous and remote diabetics management [45]. With the advent of non-invasive glucose monitoring approaches, like using saliva, sweat or tear-based biosensors, patient compliance is further improved by the frequent blood sampling being removed. These represent a big shift toward the development of user and personalized diabetes monitoring systems.

Advanced Point-of-Care Diagnostics

With the integration of nanotechnology, point-of-care diagnostics has revolutionized detection of diabetes in the blood by making the analysis rapid and relatively inexpensive. Metal nanoparticles and quantum dots are used to enhance glucose assays via nanoamplification to develop highly sensitive and selective glucose detection [46]. This can be achieved with lab-on a chip technology including nanostructured microfluidic platforms and can be performed with fast reading, the sample volume required is minimum. AI driven algorithms are further incorporated in nano diagnostics to improve the interpretation of the data and real time disease monitoring in such a way as to initiate personalized diabetes care. Also, the integration of nano biosensors with smartphone eliminates the need of patients to visit a laboratory for monitoring glucose. The changes that have been seen in nano-diagnostics with respect to these diagnostics improve early detection and make it possible for continuous disease monitoring and thus reduce complications that arise from bad glycemic control [47].

Nano-Based Therapeutics for Diabetes Treatment

Nanotechnology has provided diabetes treatment with a great leap forward of drug bioavailability, insulin delivery, as well as targeted therapeutic strategy. However, the conventional diabetes treatment methods, like subcutaneous insulin injections and oral anti diabetic drugs, are limited by poor bioavailability, enzymatic degradation, non-specific drug distribution and patient noncompliance [48]. Finally, the advances in drug delivery systems that have been developed for the development of nano based therapeutics include insulin loaded nanocarriers, regenerative nanomedicine and non-insulin based nano formulations. Thes nanocarriers improve drug stability, extend circulation time, enhance cellular uptake and control the release of the drug thus improving therapeutic efficacy and reducing the side effects at the system level. In addition, nanoparticle delivery is also site specific towards pancreatic beta cells and may aid in beta cell regeneration and restoration of insulin secretion [49]. Precise controlled insulin release of the integration of smart delivery systems based on glucose glucose responsive nanocarriers leads to reduced risk of hypoglycemia and positive glycemic stability. More biocompatible and long living formulations were designed incorporating biomaterials, such as hydrogels, degradable polymers, and lipid based nanocarriers. The nano-based therapeutic approaches used to treat diabetes are summarized in Table 3 and Figure 1 along with advantages, mechanisms of action and clinical applications [50].

Table 3. Nano-based therapeutic strategies for diabetes treatment.

Nano-Therapeutic Approach	Nanomaterial Used	Drug Delivery Mechanism	Advantages	Clinical Application	Reference
Insulin Nanocarriers	Polymeric nanoparticles, Liposomes, Hydrogels, Solid lipid nanoparticles	Encapsulation and sustained release	Enhanced bioavailability, controlled insulin release, reduced injection frequency	Insulin therapy for type 1 and advanced type 2 diabetes	[51]
Oral Insulin Delivery	Chitosan nanoparticles, Lipid-based nano-emulsions, Mucoadhesive polymers	Overcoming enzymatic degradation and enhancing intestinal absorption	Non-invasive administration, improved patient compliance	Alternative to injectable insulin for type 1 and 2 diabetes	[52]
Inhalable Insulin Nanoparticles	PEGylated nanoparticles, Lipid-based carriers, Dry powder nanocrystals	Pulmonary absorption via alveolar capillaries	Rapid insulin action, needle-free administration, improved pharmacokinetics	Postprandial glucose control in type 1 and type 2 diabetes	[53]
Stem Cell-Loaded Nanoparticles	Biodegradable polymeric carriers, Mesenchymal stem cells (MSC)-derived exosomes	Pancreatic beta-cell regeneration and immunomodulation	Beta-cell repair, restoration of insulin production, potential long-term cure	Regenerative diabetes therapy for type 1 diabetes	[54]
Gene-Based Nanotherapies	CRISPR-loaded nanoparticles, RNA-based nanocarriers, Viral vector-mediated gene delivery	Targeted gene modulation and beta-cell protection	Precision medicine, reversal of insulin resistance, beta-cell function improvement	Genetic therapy for monogenic and insulin-resistant diabetes	[55]
Phytochemical-Loaded Nanocarriers	Polymeric micelles, Nanoliposomes, Lipid-based vesicles	Increased bioavailability and stability of plant-derived anti-diabetic compounds	Antioxidant, anti-inflammatory effects, natural alternative to synthetic drugs	Herbal-based diabetes treatment and adjunct therapy for type 2 diabetes	[56]
Non-Insulin Anti-Diabetic Drug Nanocarriers	Lipid nanoparticles, Dendrimer-based formulations, Polymeric drug-loaded nanoparticles	Controlled and sustained release of oral hypoglycemic agents (e.g., metformin, GLP-1 analogs)	Improved pharmacokinetics, reduced side effects, enhanced therapeutic index	Oral anti-diabetic drug formulations for type 2 diabetes	[57]
Nanoformulations for Diabetic Complications	Polymeric nanoparticle-based antioxidants, Nanocurcumin, Nanocoenzyme Q10	Targeted drug delivery to affected organs	Reduced oxidative stress, protection against neuropathy, nephropathy, retinopathy	Adjunct therapy for diabetes-related complications	[58]

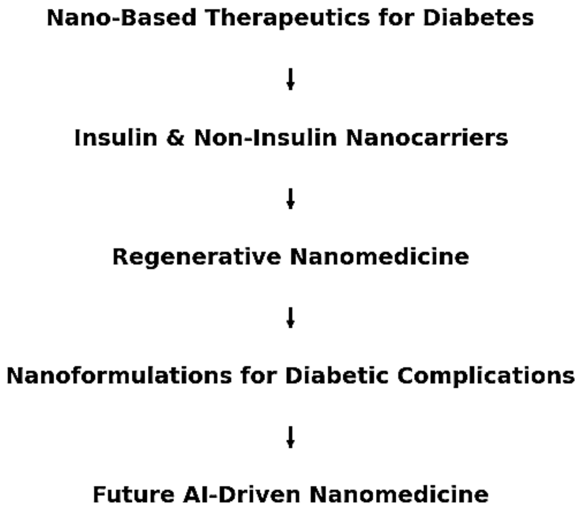

Figure 1. Nano-based therapeutics for diabetes treatment.

Insulin Nanocarriers for Improved Delivery

The ability and realization of nanotechnology has allowed for the targeted, sustained and controlled release of insulin, making the revolution of current insulin therapies a reality. Protection of insulin from enzymatic degradation, improved absorption and increased bioavailability of insulin is achieved using insulin loaded nanocarriers including polymeric nanoparticles, liposomes, hydrogels; Administration of insulin more frequently may be avoided because of encapsulation in polymeric carriers that prolong circulation [59]. The use of chitosan and lipid-based carriers for oral insulin formulation allows for the bypass of harsh gastric environment leading to intestinal absorption and improving patient compliance and hypoglycemia risk. In addition, inhalable insulin nanoparticles provide an alternative to subcutaneous injections without having to intrude and can give rapid action by pulmonary absorption. Created nanocarriers for smart insulin designed for triggering insulin release based on changes in glucose levels and mimic the glucose regulator function of pancreatic beta cells. Such advancements lead to enhanced glycemic control, reduce the patient discomfort, and promote adherence to insulin therapy. In future, progress will be made in nanotechnology that can result in self-regulating insulin systems with ultra long-acting profiles [60].

Regenerative Nanomedicine for Diabetes

Diabetes treatment through regenerative nanomedicine is expected to decrease, and restore pancreatic beta cell function, while increasing insulin secretion. Potential cure for diabetes is promoted by stem cell loaded nanoparticles encapsulated in biodegradable polymeric carriers that are employed to regenerate pancreatic cells [61]. Mesenchymal stem cell derived exosomes have been placed in nanoparticles and shown to have immunomodulatory effects leading to reduction of autoimmune destruction in type 1 diabetes. Nanomedicine based on exosome has also been attracting attention for beta cell repair by targeting nanosized extracellular vesicles for cellular communication and increasing beta cell viability and function. Nanotherapies based on genes or RNA include CRISPR nanoparticles loaded with specificity for gene editing and correction of the genetic defects involved in insulin resistance and beta cell dysfunction. A goal for these regenerative strategies is to achieve long term glycemic control without dependence on exogenous insulin and prevent diabetes progression [62]. The future work in regenerative nanomedicine will be done regarding optimizing stem cell differentiation, beta cell transplantation outcomes, and gene therapies for sustained insulin production.

Non-Insulin Nano-Therapeutics

Nanotechnology has enabled the advancement of ultra-drug delivery systems for non-insulin diabetes treatment. Formulations of anti-diabetic drugs based on nanoparticles (NPs) of metformin, GLP-1 analogs and SGLT2 inhibitors improve the drug stability, solubility and absorption while allowing for better therapeutic outcomes. Nanocarriers containing phytochemicals from plant sources, e.g. curcumin, quercetin, and resveratrol act as excellent carriers of anti-inflammatory, antioxidant, and insulin sensitizer, with natural approaches to diabetes management. Furthermore, nanomedicine targeting diabetic complications, such as neuropathy, nephropathy, and retinopathy has potential for minimizing result of long-term diabetes related damage [63]. A new generation of therapeutic approaches are having an impact to devise more efficient and personalized management of diabetes. In the future, these new avenues will be pursued to determine the contribution of surface modifications of the nanocarrier and ligand-targeted drug delivery and AI optimization of nanoparticle formulations to precision medicine in the treatment of diabetes [64].

FUTURE TRENDS AND CHALLENGES IN NANO-THERAPEUTICS FOR DIABETES

Regulatory Hurdles and Safety Concerns of Nano-Drug Formulations

Nanotechnology based drug formulations offer great promise for treatment of diabetes but have some important regulatory and safety challenges before clinical translation. Nanoparticles have unique physicochemical properties, rendering application of the traditional pharmacokinetic and toxicological assessment methods incomplete if one desires to examine long term impacts. Biocompatibility, minimization of nanoparticle accumulation in off target organs and assessment of possible immunogenic reaction need to be assured [65]. However, preliminary guidelines have been developed by regulatory agencies, like the US Food and Drug Administration or the European Medicines Agency, but one does not exist globally. Robust pre-clinical studies, computational modeling and artificial intelligence driven safety assessment are needed to address these concerns and is necessary to speed up the approval process. This necessitates both an integrated approach in analytical technique coupled with computational modeling and continuous manufacturing to ensure the stability of the nanoparticle and efficacy during the regulatory compliance. Table 4 and Figure 2 demonstrate these strategies to increase the scalability and reproducibility of nano-therapeutics as well as address potential safety concerns and regulatory acceptance [66].

Table 4. Regulatory considerations and safety concerns in nano-therapeutics for diabetes.

Challenge	**Description**	**Potential Solutions**	**Reference**
Long-term toxicity	Accumulation of nanoparticles in non-target tissues	Use of biodegradable polymers, real-time imaging techniques	[67]
Lack of standardized regulations	Variability in global regulatory guidelines	Development of harmonized international standards	[68]
Immunogenicity concerns	Risk of immune system activation by nanoparticles	Surface modification, PEGylation strategies	[69]
Stability and shelf-life	Degradation of nanomedicine formulations over time	Optimized storage conditions, lyophilization methods	[70]
Reproducibility issues	Batch-to-batch variations affecting therapeutic outcomes	Scalable manufacturing processes, AI-driven quality control	[71]

Clinical Translation and Commercialization Challenges

The number of preclinical studies of nano based therapeutics for diabetes continues to rise, few of these nanotherapeutics make it from the bench into clinical application. This slow commercialization process is caused by the high cost of nanotechnology research as well as the lack of large-scale production facilities and the requirement of long-term clinical trials. However, pharmaceutical companies must continuously invest in scalable and affordable manufacturing technologies, such as microfluidic nanoprecipitation and continuous flow synthesis to make sure they are reproducible and affordable [72]. Additionally, the studies by academic research institutions in cooperation with biotechnology firms and with the relevant regulatory agencies may accelerate the clinical development pipeline and consequently shorten the gap before market introduction. Commercialization efforts are further complicated by the need for harmonized global regulatory frameworks and well-defined approval pathways. Bringing experimental research to real world clinical applications should require developing strategic partnerships as well as getting funding for large scale clinical trials [73].

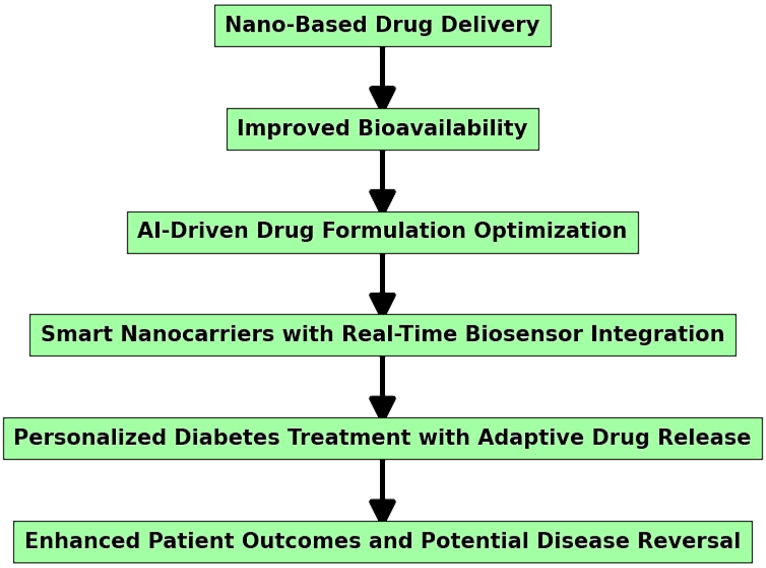

Figure 2. Evolution of nano-therapeutics in diabetes management.

Future Perspectives: AI-Driven and Personalized Nanomedicine for Diabetes

Artificial intelligence integrated with nanotechnology is going to change the way of personalized diabetes management. Predictive nanoparticle formulation can make use of AI to improve drug stability, bioavailability, etc. This allows for machine learning algorithms to study real time biosensor data and can be treated in crude terms, to allow adaptive drug delivery systems that can change insulin release based on glucose changes. Moreover, nanotherapies using CRISPR-based gene editing and stem cells housed in nanoparticles for the development of patient specific nanotherapies could be used for cure diabetes in the future [74]. A paradigm shift of the diabetes care from symptom to disease reversal may be achieved with the convergence of artificial intelligence (AI), nanomedicine, and regenerative therapies.AI enhanced personalized medicine is outlined to transform the evolution of nano-therapeutics in diabetes treatment and realize conventional drug delivery to deactivate disease-producing technology and address pesky, botched surgery, or cancerous reoccurrence syndrome. Precision real time management of blood glucose levels can be possible by developing a smart nanocarrier which is equipped with a biosensor and AI controlled drug release system that can help to minimize complications and improve patient adherence to treatment. The future of nanomedicine in relieving diabetic pathology will be to have combinations of all therapies, like gene editing and tissue engineering, that can provide long term cure for the disease [75].

CONCLUSIONS

The advancement of nanotechnology has succeeded to revolutionize the diabetes management by enhancing the diagnostic tools, creating systemically efficient delivery of drugs and tailoring patient's therapeutic solutions. Nano based biosensors, smart insulin nanocarriers and regenerative nanomedicine have significantly contributed in the development of glucose monitoring, insulin administration and pancreatic regeneration, respectively. However, nano-therapeutics have several limitations, including enhancing drug bioavailability, reducing systemic side effects, enabling real-time disease management, improving drug delivery effectiveness and resolving the constraints of conventional diabetes treatments. The combination of artificial intelligence with nanomedicine represents a future approach that, among other things, enables treating based on real time data driven treatment strategies and adaptive drug delivery. The next frontier in the field of diabetes care is personalized medicine based on machine learning and CRISPR based gene therapy that moves away from symptom management to potential disease reverse. The current limitations to overcome for the successful transition of nano based therapies in experiment research into clinical applications would be continued inter disciplinary collaboration between researchers, clinicians and regulatory agencies. With future developments in nanotechnology, the future diabetes cure will trend more toward smart and adaptive, and personalized to the patients with diabetes. The aim is, therefore, to realize long term glycemic control, decrease diabetes related complications, and enhance the quality of life for the patients globally.

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