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REVIEW

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Silver nanoparticles in diabetes mellitus: therapeutic potential and mechanistic insights

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Abstract

Background Research on the use of silver nanoparticles in the context of diabetes mellitus has gained attention due to the unique properties of these nanoparticles, such as their antimicrobial, anti-inflammatory, and antioxidant characteristics. While the field is still in its early stages, several studies have explored the potential applications and effects of silver nanoparticles in managing diabetes.

Main body of the abstract Diabetes mellitus, a global health concern marked by impaired insulin function and high blood glucose levels, has spurred innovative therapeutic investigations, including nanotechnology. Silver nanoparticles have emerged as promising candidates in this pursuit. This abstract provides an overview of current research on silver nanoparticles' application in managing diabetes mellitus, highlighting their therapeutic potential and mechanisms of action. With unique physicochemical properties like high surface area and bio-compatibility, silver nanoparticles are ideal for diverse biomedical applications. Recent studies show their ability to modulate key pathways in diabetes pathogenesis, enhancing insulin sensitivity, reducing oxidative stress, and supporting pancreatic beta-cell function. Their antimicrobial properties are particularly beneficial for diabetes patients prone to infections. Moreover, using silver nanoparticle-based carriers for anti-diabetic drugs improves drug bio-availability and reduces side effects, potentially enhancing conventional medication efficacy. However, addressing safety and toxicity concerns is crucial. Ongoing research focuses on optimizing nanoparticle size, shape, and surface modifications to enhance bio-compatibility and minimize adverse effects.

Short conclusion In conclusion, silver nanoparticles represent a novel and multifaceted approach in the management of diabetes mellitus. Their ability to target multiple facets of diabetes pathogenesis, including insulin resistance, oxidative stress, and inflammation, positions them as potential candidates for future therapeutic interventions. However, further research is warranted to elucidate their long-term safety profile and optimize their application in clinical settings.

Keywords Anti-diabetic activity, Diabetes mellitus, Therapeutic potential, Silver nanoparticles, Characterization methods

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Background

It was the search for novel, effective, and targeted treatments for the complex pathophysiology of diabetes that led to the utilization of silver nanoparticles. Because of their one-of-a-kind characteristics, silver nanoparticles have the potential to revolutionize diabetes treatment by targeting a wide variety of disease factors through innovative processes. Having diabetes mellitus, which is defined by decreased insulin action and increased blood glucose levels, is a global health concern that affects a lot of people. Silver nanoparticles have emerged as viable options as a result of the research of nanotechnology, which has been prompted by the search for novel and efficient therapeutic strategies. In this article, an overview of the current research on the application of silver nanoparticles in the management of diabetes mellitus is presented. The article also highlights the therapeutic potential of these nanoparticles as well as the underlying processes upon which they act. Due to their exceptional physicochemical qualities, which include a high surface area, increased reactivity, and bio-compatibility, silver nanoparticles are ideally suited for a wide range of applications in the field of bio-medicine. Recent research has shown that silver nanoparticles have the ability to modify critical pathways that are involved in the etiology of diabetes. The anti-diabetic effects of these nanoparticles have been demonstrated to be achieved by the enhancement of insulin sensitivity, the reduction in oxidative stress, and the promotion of pancreatic beta-cell activity. The antibacterial capabilities of silver nanoparticles are especially remarkable in the context of diabetes, which is characterized by an increased susceptibility to infections. Additionally, silver nanoparticles have been explored for their anti-inflammatory effects, with the goal of addressing the chronic low-grade inflammation that is associated with issues related to diabetes. As an additional point of interest, the administration of anti-diabetic medications through carriers based on silver nanoparticles has demonstrated potential in terms of enhancing drug bio-availability and minimizing adverse effects. The utilization of this strategy has the potential to improve the effectiveness of traditional anti-diabetic drugs. Concerns regarding the safety and toxicity of silver nanoparticles must be addressed immediately, despite the fact that the therapeutic effects of silver nanoparticles are quite promising. Research is now being conducted with the goal of improving the bio-compatibility of these nanoparticles by optimizing their size, shape, and surface changes. This is being done in order to avoid any potential detrimental effects.

Main text

The field of nanoscience and nanotechnology has brought about significant advancements in disease diagnosis, treatment, and prevention across various domains. The utilization of silver for wound cleansing and infection management can be traced back to ancient times. The distinct characteristics of silver nanoparticles (AgNPs) have gained substantial recognition in the field of therapeutics, making them the preferred choice among metallic nanoparticles (Zimkhitha et al. 2021). The subject under investigation exhibits remarkable characteristics in terms of chemical stability, catalytic properties, and conductivity, as well as noteworthy anti-diabetic, antimicrobial, and anti-inflammatory activities. The utilization of silver therapy has been found to yield numerous advantageous outcomes, encompassing a multifaceted anti-diabetic mechanism, efficacy against drug-resistant organisms, and minimal systemic toxicity (Habeeb Rahuman et al. 2022).

Diabetes mellitus type 2, also known as T2DM, is a prevalent metabolic imbalance where the body produces insufficient insulin, leading to elevated blood glucose levels. Type 2 diabetes mellitus is an abbreviated term used to describe a long-term metabolic condition that is marked by elevated levels of sugar in the blood (Wahab et al. 2022). T2DM has emerged as a significant contributor to various adverse health outcomes, including stroke, amputation, kidney failure, heart attack, and blindness. These complications have garnered considerable attention due to their substantial impact on individuals affected by T2DM. This paper intends to explore the connection between T2DM and the aforementioned health consequences, shedding light on the gravity of this disease and the urgent need for effective prevention and management strategies. Through an examination of existing literature and research findings, the main objective of this paper is to present a comprehensive understanding of the detrimental effects of T2DM on stroke, amputation, kidney failure, heart attack, and according to recent research, it has been determined that this particular phenomenon is not only a prevalent issue, in addition, it also holds the notable distinction of being the seventh biggest prominent contributor to global mortality (Ferdous et al. 2019). The research paper aims to explore the various significant risk factors associated with a particular health condition. The factors under investigation include obesity, inflammation, inactivity, stress, and genetics. These factors have been identified as potential contributors to the development or exacerbation of the health condition in question. By examining these risk factors, we hope to obtain a deeper knowledge of their individual and collective impact on the overall health outcomes of individuals. The influence of environmental factors on the manifestation of type 2 diabetes mellitus genes are of considerable significance. The adoption of a healthy lifestyle has been identified as a potential precautionary steps against the onset of Type 2 diabetes mellitus (T2DM) in certain susceptible individuals. Conversely, engaging in unhealthy practices has been linked to a higher chance of developing T2DM in non-susceptible individuals. The review paper aims to investigate the connection between lifestyle choices and the development of T2DM, highlighting the importance of adopting healthy habits to mitigate the risk of this chronic condition. The consumption of unhealthy diets characterized by elevated levels of saturated fat and inadequate fiber intake has been identified as a major factor that greatly increases the risk of developing metabolic disorders, including cardiovascular problems and type 2 diabetes mellitus. The presence of obesity, particularly in individuals with a familial predisposition to T2DM, significantly augments the probability of developing this metabolic disorder. The phenomenon of obesity entails the enlargement of adipocytes, which subsequently leads to metabolic alterations and an augmented discharge of free fatty acids and glycerol via heightened lipolysis. This, in turn, gives rise to a state of insulin resistance within muscles. The management of T2DM can be achieved through the utilization of both pharmacological interventions and lifestyle modifications. This paper aims to explore the efficacy of drugs and lifestyle changes in the management of T2DM without introducing any additional information. T2DM, a persistent chronic condition that involves insulin resistance and impaired control of glucose in the body, necessitates a comprehensive approach to treatment. Pharmacological interventions play a crucial role in managing T2DM by targeting Exercise has been identified as the primary therapeutic intervention for the management of hyperglycemia. The purpose of the study is to explore the impacts of increased physical activity on glucose regulation and insulin sensitivity. It is extensively recognized that engaging in regular physical activity is vital for maintaining overall health and also reducing the risk of chronic diseases. In particular, the impact of physical activity on glucose regulation and insulin sensitivity has been extensively studied due to their significance in the development and management of conditions such as diabetes. Numerous studies have consistently demonstrated that increased physical activity leads to improvements. Dealing with type 2 diabetes mellitus (T2DM) encompasses a wide range of pharmacological interventions. These interventions include the administration of various drugs, such as Metformin, Sulfonylureas, Thiazolidinedione, Repaglinide, and α-Glucosidase inhibitors. Each of these drugs plays a distinct role in the management of T2DM and is associated with specific mechanisms of action and therapeutic benefits. By understanding the characteristics and effects of these drugs, healthcare professionals can make informed decisions regarding their use in the treatment of T2DM. The therapeutic effects of metformin in the management of hyperglycemia have been extensively studied and documented. Metformin, a widely prescribed oral anti-diabetic medication, has been shown to effectively lower blood glucose levels through its multifaceted mechanisms of action. This research paper aims to elucidate the primary mechanisms by which metformin exerts its glucose-lowering effects. One-way metformin works to lower blood glucose levels is by inhibiting the liver's production of glucose. To maintain glucose balance, the liver plays a vital role by producing glucose through a process known as gluconeogenesis. Metformin acts by inhibiting key enzymes involved in gluconeogenesis, such as phosphoenolpyruvate carboxykinase (PEPCK) and glucose-6-phosphatase. G Sulfonylureas have been identified as agents that effectively stimulate insulin secretion, thereby aiding in the management of diabetes mellitus. However, it is important to note that the administration of sulfonylureas may also give rise to hypoglycemia, which is recognized as a possible adverse reaction. Thiazolidinedione increases receptor molecules like peroxisome proliferator-activated receptors, which regulate fat and glucose metabolism. However, it has been observed that the administration of this treatment may lead to the occurrence of certain undesirable outcomes, such as heightened edema and cognitive heart failure. The pharmacological agent repaglinide has been found to exhibit the ability to stimulate insulin secretion before meals. However, it is important to note that repaglinide possesses a shorter half-life in comparison with sulfonylureas. α-Glucosidase inhibitors have been found to exert a notable impact on glucose digestion within the intestine, consequently leading to a reduction in postprandial blood glucose levels (Choi et al. 2018). Metformin is a widely utilized medication; however, its efficacy is hindered by its slow mechanism of action and the occurrence of side effects, leading to suboptimal therapeutic outcomes. This paper aims to explore the limitations associated with Metformin, shedding light on its delayed mode of action and the adverse effects it may induce. By examining these factors, we can get a complete grasp of the situation of the challenges posed by Metformin in achieving desirable therapeutic responses. Metformin, a common medication given by a doctor, is primarily employed in the management of type 2 diabetes mellitus. Its mechanism involves reducing the production of glucose in the liver and improving the sensitivity of peripheral tissues to insulin (Foretz et al. 2019). Despite its widespread use, the therapeutic response to Metformin is often unsatisfactory due to its slow onset. In light of the escalating incidence of drug-resistant diabetes, it is imperative to promptly undertake measures in the management of this condition (Wahab et al. 2022) in response to the aforementioned constraints, and researchers have undertaken the development of Nanomedicine. In recent years, there has been a lot of popularity around nanotechnology because of its exciting applications in many different areas, including health services. One area of particular interest is the management of diabetes, a chronic disease that affects millions of individuals worldwide. Experts have examined the application of nanotechnology in developing innovative approaches for diabetes management. Silver nanoparticles have received a lot of attention in the field of medicine and pharmaceuticals due to their distinctive physicochemical properties. These nanoparticles, composed of silver atoms, exhibit a wide range of characteristics that make them highly attractive for various applications in these domains. The unique properties of silver nanoparticles have been extensively studied and have demonstrated great potential for advancements in medical and pharmaceutical fields (Wahab et al. 2022). The management of diabetes necessitates the implementation of various strategies, one of which involves the prevention of alpha-amylase and glucosidase enzyme activity. Alpha-amylase and glucosidase enzymes play a crucial role in the breakdown of complex carbohydrates into simple sugars, thereby facilitating their absorption in the body. However, in individuals with diabetes, the excessive activity of these enzymes can lead to rapid and uncontrolled glucose release, resulting in elevated blood sugar levels. Consequently, inhibiting the activity of alpha-amylase and glucosidase enzymes has emerged as a pivotal approach in the management of diabetes. By impeding the enzymatic breakdown of carbohydrates, the inhibition of amylase and glucosidase enzymes has been demonstrated to have a critical role in preventing of carbohydrate breakdown, consequently mitigating the risk of elevated blood glucose levels. Silver nanoparticles have been identified in various studies as potential alpha-amylase inhibitors, as demonstrated in both in vitro and in vivo experimental settings (Nie et al. 2023).

Future prospective of treatment for diabetes

The future prospects of diabetes treatment hold promise as researchers explore innovative approaches and technologies. Potential avenues for advancements including tailoring diabetes treatment based on individual genetic and molecular profiles may become more common, allowing for personalized and targeted therapies. Ongoing research focuses on developing more sophisticated insulin delivery methods, such as smart insulin pumps, closed-loop systems, and implantable devices to enhance precision and convenience. Stem cell research holds potential for regenerative medicine in diabetes. Scientists are exploring ways to regenerate insulin-producing beta cells to restore normal insulin function. Genetic interventions may offer new possibilities for addressing the root causes of diabetes. Research in gene editing technologies and gene therapy aims to correct genetic mutations associated with diabetes. The integration of AI and machine learning in diabetes management is anticipated to improve predictive modeling, personalized treatment plans, and real-time monitoring, enhancing overall disease management. Continued exploration of nanotechnology, including the use of nanoparticles for drug delivery and diagnostics, may lead to more effective and targeted treatments with reduced side effects. Researchers are investigating immunotherapies that modulate the immune system to prevent or slow down the autoimmune response responsible for type 1 diabetes. Advancements in identifying novel biomarkers for diabetes risk, progression, and complications can enable early detection and intervention strategies, potentially preventing or delaying the onset of the disease. Integration of digital health technologies, mobile applications, and wearable devices will likely play a significant role in lifestyle interventions, supporting individuals in managing their diabetes through real-time monitoring and personalized feedback. Efforts to improve global collaboration, access to healthcare, and affordability of diabetes treatments will be crucial in ensuring that advancements in diabetes care reach diverse populations worldwide.

The therapeutic agents' thiazolidinedione, sitagliptin, alogliptin, canagliflozin, SGLT2 inhibitors, and exenatide have demonstrated efficacy in the treatment of various medical conditions, including heart failure, hypoglycemia, urogenital tract infections, and balanoposthitis in both male and female patients (Kose et al. 2023). These pharmacological interventions have been extensively studied and have shown promising results in managing these specific health concerns. The phenomenon of excessive antibody production has been observed to have deleterious effects on patients receiving injectable medications such as RA-GLP1. These effects manifest in the form of abscess formation, cellulitis, and necrosis (Husain et al. 2023). The administration of insulin through injections has been associated with several physiological effects, including weight gain, hyperinsulinemia, and hypoglycemia. These outcomes have been observed in individuals who rely on insulin therapy for the treatment of diabetes mellitus. The purpose of this paper is to explore the existing literature on the relationship between insulin injections and the aforementioned effects, shedding light on the potential implications for patients undergoing insulin treatment. By the future trajectory of diabetes treatment is anticipated to exhibit a heightened emphasis on personalized approaches that consider a person's specific genes and lifestyle choices and specific requirements. In recent years, significant progress has been made in the field of genomics and data analysis, offering promising prospects for the identification of optimal medications or interventions tailored to individual patients (Das et al. 2022). This research paper aims to explore the advancements in genomics and data analysis and their potential implications for personalized medicine. The study of an organism's complete set of DNA, also known as Genomics, has completely transformed how we grasp human health and disease. The completion of the Human Genome Project in 2003 marked a pivotal moment in genomics, providing researchers with a comprehensive reference for the human genome. Since then, technological advancements and cost reductions in DNA sequencing have facilitated the generation of vast amounts of genomic data, enabling researchers to delve deeper into the genetic basis of diseases and treatment responses. Data analysis, on the other hand, the advancements in insulin pumps and continuous glucose monitoring systems have led to increased sophistication and user-friendliness. Future developments in the field of diabetes management may encompass the implementation of fully automated closed-loop systems. These systems have the potential to revolutionize insulin delivery by dynamically adjusting the dosage in real time, guided by continuous glucose monitoring. By leveraging the power of advanced algorithms and artificial intelligence, these closed-loop systems aim to optimize glycemic control and enhance patient outcomes. This paper will explore the potential benefits and challenges associated with the integration of such automated systems into diabetes care, shedding light on the future direction of this promising area of research. The investigation conducted by researchers involved an examination of cell-based therapies, specifically focusing on beta-cell transplantation, as a potential method for the replacement of impaired or non-operational pancreatic cells in individuals diagnosed with type 1 diabetes. The potential of this intervention to offer a lasting remedy is noteworthy. The ongoing progress in the field of medical technology has led to the development of artificial pancreas systems, which integrate insulin pumps and continuous glucose monitors. These systems aim to provide a more efficient and effective method for managing blood glucose levels in individuals with diabetes (Hu et al. 2023). The implementation of effective weight management strategies, adoption of dietary modifications, and engagement in regular physical activity have been found to have a substantial impact on mitigating the risk of disease development. In the context of type 1 diabetes, there has been considerable interest in investigating immunotherapies as a means to regulate the immune response and attenuate the autoimmune-mediated deterioration of beta cells. It is crucial to acknowledge that the domain of diabetes treatment is subject to continuous evolution, with the potential emergence of novel breakthroughs and treatments after the most recent update (Wang et al. 2020).

The field of nanoscience and nanotechnology have definitely had a major impact on disease diagnosis, treatment, and prevention across various domains of human existence. The utilization of silver for wound cleansing and infection management dates back to ancient times. Silver nanoparticles (AgNPs) have garnered considerable attention in the field of therapeutics due to their distinctive properties, making them a preferred choice among metallic nanoparticles. The subject under investigation exhibits extraordinary chemical stability, catalytic characteristics, conductivity, as well as notable anti-diabetic, antimicrobial, and anti-inflammatory properties. The utilization of silver therapy has been found to yield numerous advantageous outcomes, encompassing a wide range of effects such as multilevel anti-diabetic action, efficacy against drug-resistant organisms, and minimal systemic toxicity (Zimkhitha et al. 2021).

Diabetes mellitus type 2 (T2DM) is a prevalent metabolic disorder characterized by elevated blood glucose levels resulting from diminished insulin secretion. Type 2 diabetes mellitus, commonly referred to as T2DM, and is an abbreviated term used in the medical field (Wahab et al. 2022). Type 2 diabetes mellitus (T2DM) has emerged as a significant contributor to various debilitating health complications, including stroke, amputation, kidney failure, heart attack, and blindness (Ferdous et al. 2019). This research paper aims to explore and analyze the various significant risk factors associated with a particular health condition. In this case, the focus is on identifying and understanding the risk factors that contribute to the development and progression of the condition. The factors that have been identified as significant in this context include obesity, inflammation, inactivity, stress, and genetics. By examining these risk factors, researchers and healthcare professionals can gain valuable insights into the etiology and pathogenesis of the condition, ultimately leading to the development of effective The influence of environmental factors on the manifestation of type 2 diabetes mellitus (T2DM) genetic predisposition is of paramount importance (Wang et al. 2020). The adoption of a healthy lifestyle has been shown to have a preventive effect on the development of Type 2 Diabetes Mellitus (T2DM) in certain individuals who are susceptible to the disease. Conversely, engaging in unhealthy practices has been found to contribute to the onset of T2DM in individuals who are not inherently susceptible to the condition. The consumption of unhealthy diets characterized by elevated saturated fat content and insufficient fiber levels has been identified as a significant factor contributing to the development of metabolic disorders, including cardiovascular problems and type 2 diabetes mellitus (T2DM). The presence of obesity, particularly among individuals with a familial predisposition to type 2 diabetes mellitus (T2DM), has been shown to elevate the probability of developing this metabolic disorder. The phenomenon of obesity entails the enlargement of adipocytes, which subsequently leads to metabolic alterations and an augmented release of free fatty acids and glycerol via heightened lipolysis. The initial course of action for managing hyperglycemia typically involves engaging in physical exercise. The present study aims to investigate the effects of increased physical activity on glucose regulation and insulin sensitivity. It is widely recognized that physical activity plays a crucial role in maintaining overall health and well-being. In particular, numerous studies have suggested a positive association between physical activity and glucose regulation, as well as insulin sensitivity. Glucose regulation refers to the body's ability to maintain stable blood glucose levels within a narrow range. The management of type 2 diabetes mellitus (T2DM) encompasses a wide range of pharmacological interventions. These interventions include the administration of several drugs, namely Metformin, Sulfonylureas, Thiazolidinedione, Repaglinide, and α-Glucosidase inhibitors. The purpose of this study is to investigate the effects of metformin on blood glucose levels. Metformin is a commonly prescribed medication for the treatment of type 2 diabetes. It has been shown to effectively lower blood glucose levels through various mechanisms. One of the primary mechanisms by which metformin exerts its glucose-lowering effects is by suppressing liver glucose production. The liver plays a crucial role in maintaining blood glucose homeostasis by producing glucose through a process called gluconeogenesis. Metformin inhibits this process, thereby reducing the amount of glucose released into the bloodstream. In addition to its impact on liver glucose production, metformin also enhances glucose uptake in cells. This is achieved through the activation of a key cellular enzyme called AMP-activated protein kinase (AMPK). AMPK is a master regulator of sulfonylureas have been found to possess the ability to stimulate the secretion of insulin, thereby enhancing glucose control in individuals with diabetes. However, it is important to note that the administration of sulfonylureas may also give rise to the potential occurrence of hypoglycemia as an adverse effect. The administration of thiazolidinedione has been found to induce an up-regulation of receptor molecules, such as peroxisome proliferator-activated receptors (PPARs), which play a crucial role in the regulation of fat and glucose metabolism. However, it has been observed that the administration of this treatment may lead to the occurrence of certain undesirable outcomes, such as heightened edema and cognitive heart failure (Lekamge et al. 2019). The present study aims to investigate the effects of repaglinide on insulin secretion prior to meals, while also comparing its half-life to that of sulfonylureas. Repaglinide, a medication commonly used to treat type 2 diabetes, has been found to exhibit the ability to stimulate insulin secretion. This effect is particularly notable when administered before meals, suggesting its potential as a therapeutic option for managing postprandial hyperglycemia. In comparison with sulfonylureas, repaglinide demonstrates a shorter half-life. Sulfonylureas, a α-Glucosidase inhibitors, have been found to exert a notable impact on glucose digestion within the intestine, consequently leading to a reduction in postprandial blood glucose levels (Choi et al. 2018). Introduction Metformin is a widely utilized medication due to its effectiveness in managing various medical conditions. However, despite its common usage, the drug's slow mode of action and associated side effects have been found to contribute to a suboptimal therapeutic response. This paper aims to explore the limitations of Metformin in terms of its delayed onset of action and the adverse effects it may induce, ultimately leading to a less-than-satisfactory treatment outcome. Delayed onset of action, one of the primary concerns associated with Metformin, is its slow mode of action. While the drug is recognized for its efficacy in managing conditions such as type 2 diabetes, it often requires a significant amount of time to exhibit its full therapeutic effects. This delayed onset of action can be attributed to various factors, including the drug's pharmacokinetic properties and In light of the escalating incidence of drug-resistant diabetes, it is imperative to promptly undertake measures in the management of this condition (Wahab et al. 2022).

In order to address the aforementioned limitations, researchers are actively engaged in the development of a field known as Nanomedicine. The field of nanotechnology has been extensively investigated in the context of diabetes management. Silver nanoparticles have garnered significant attention in the field of medicine and pharmaceuticals due to their distinctive physicochemical properties (Wahab et al. 2022). These nanoparticles, composed of silver atoms, exhibit a range of characteristics that make them highly attractive for various applications in these domains. The management of diabetes necessitates the implementation of various strategies, one of which involves the prevention of alpha-amylase and glucosidase enzyme activity. These enzymes play a crucial role in the breakdown of carbohydrates, leading to the release of glucose into the bloodstream. By inhibiting the activity of alpha-amylase and glucosidase, the rate of carbohydrate digestion and subsequent glucose absorption can be effectively regulated. This research paper aims to explore the significance of preventing the activity of these enzymes as a key strategy in managing diabetes. The utilization of amylase and glucosidase inhibitors is effective in inhibiting the enzymatic breakdown of carbohydrates, thereby mitigating the potential rise in blood glucose levels. Silver nanoparticles have been identified in various studies as potential alpha-amylase inhibitors, as demonstrated in both in vitro and in vivo experiments (Nie et al. 2023).

Potential role of silver nanoparticles for the treatment of diabetes

Silver nanoparticles (AgNPs) have garnered significant attention in the field of nanomedicine due to their unique properties and potential therapeutic applications. While there is ongoing research into the use of AgNPs in various medical fields, their role in the treatment of diabetes is still largely experimental and not yet widely established. AgNPs have demonstrated antioxidant and anti-inflammatory properties. Diabetes is characterized by oxidative stress and chronic inflammation, which contribute to complications. AgNPs could potentially help reduce these factors, providing some relief from diabetic complications. Diabetic patients are prone to slow wound healing, which can lead to serious complications. AgNPs have been investigated for their ability to enhance wound healing due to their antimicrobial properties and potential to stimulate tissue regeneration. Nanoparticles, including AgNPs, can be used as drug delivery vehicles. In the context of diabetes, they could be employed to deliver insulin or other anti-diabetic drugs in a controlled and targeted manner. This can improve the effectiveness of drug therapy and reduce side effects. AgNPs have been utilized in the development of glucose sensors. These sensors can provide real-time monitoring of blood glucose levels, which is crucial for diabetes management. The use of AgNPs in sensor technology could lead to more accurate and sensitive devices. Diabetic patients are more susceptible to infections, and AgNPs are known for their antimicrobial properties. They may help in preventing or treating infections in diabetic wounds. Some studies have suggested that silver nanoparticles may have vasodilatory effects, which could potentially be beneficial for individuals with diabetes by improving blood circulation. However, more research is needed to establish the safety and efficacy of such applications.

Silver nanoparticles (AgNPs) are used in biomedical sciences to deliver specific drugs. They are also utilized in textiles, cosmetics, food storage, deodorants, biosensors, orthopedic and cardiovascular implants, bandages, surgical catheters, wound and burn dressings, and therapeutics. Cleaning items and home products also employ them. Due to their anti-inflammatory qualities, silver nanoparticles aid burn and wound healing. Due to their strong antioxidants, plant-mediated silver nanoparticles minimize metabolic and external oxidative stress. Plant extracts' reducing compounds—phenols, flavonoids, and amides—are essential for synthesizing eco-friendly nanoparticles (Khoshnamvand et al. 2020).

Methods of silver nanoparticle preparation

There are several methods for synthesizing silver nanoparticles.

In the realm of problem-solving approaches, two prominent methods have emerged: the "top-down" and "bottom-up" approaches. These methods, which have been extensively studied and utilized in various fields, offer distinct strategies for tackling complex problems. By understanding the fundamental principles and characteristics of each approach, researchers and practitioners can effectively apply them in their respective the "top-down" approach involves the mechanical grinding of metals of significant size, accompanied by the use of a colloidal protecting agent to ensure stabilization. The "bottom-up" approach, as described in the literature (Husain et al. 2023), involves the utilization of chemical reduction, sono-decomposition, and electrochemical techniques (Konop et al. 2019).

Figure 1 represents the different methods of preparation of silver nanoparticles. The synthesis of silver nanoparticles is predominantly achieved through chemical reduction employing both organic and inorganic reducing agents. The preparation of silver nanoparticles (AgNPs) entails a chemical process that necessitates the utilization of metal precursors, reducing agents, and capping agents. The reduction of silver ions to produce metallic silver nanoparticles is a widely studied phenomenon in the field of nanotechnology. Various reducing agents, such as sodium citrate, ascorbate, and sodium borohydride ($NaBH_4$), have been employed in this process. These agents play a crucial role in facilitating the reduction reaction and controlling the size and morphology of the resulting nanoparticles. By effectively reducing silver ions, these agents promote the formation of metallic silver nanoparticles, which exhibit unique properties and find applications in various fields. The chemical synthesis of nanoparticles offers numerous advantages, including the ease of production and high yield. Nevertheless, the utilization of chemical-reducing agents in various processes can potentially pose detrimental effects on living organisms.

The production of silver nanoparticles can be achieved through various physical methods, such as laser ablation and evaporation–condensation. These techniques have been extensively studied and employed in the synthesis of silver nanoparticles. Laser ablation involves the use of high-energy laser pulses to ablate a silver target, resulting in the formation of nanoparticles. On the other hand, evaporation–condensation entails the evaporation of a

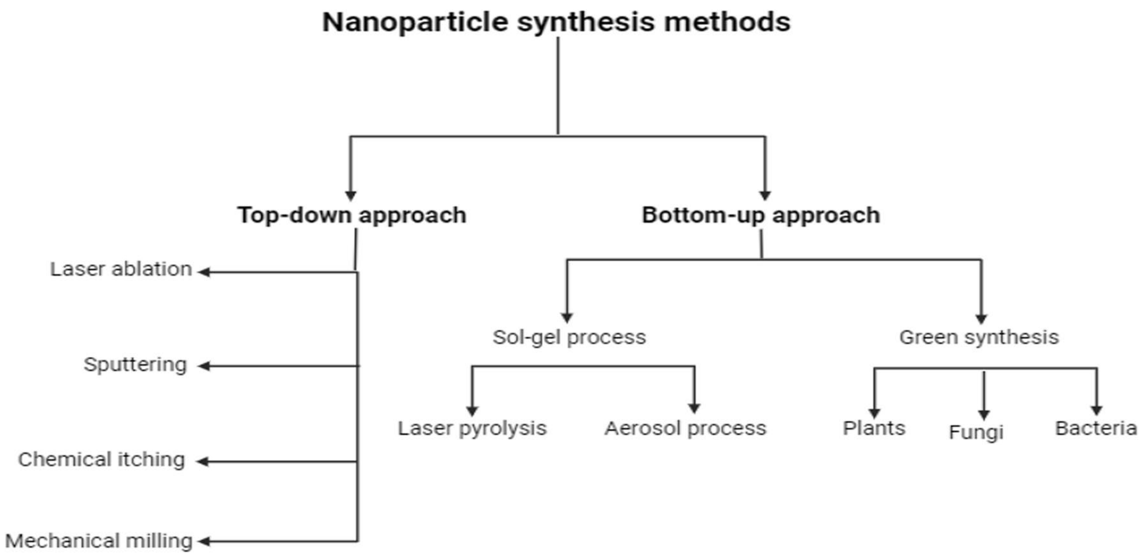

Fig. 1 Different methods for the nanoparticle synthesis

silver precursor followed by its condensation into nanoparticles. These physical methods offer distinct advantages in terms of control over particle size, shape, and purity. Consequently, they have emerged as valuable approaches for the fabrication of silver nanoparticles in diverse applications. Physical synthesis methods have been widely recognized for their numerous advantages in various fields of research and industrial applications. One notable advantage is the ability to produce solvent-free thin films, which has garnered significant attention due to its potential for addressing environmental concerns associated with solvent usage. The absence of solvents not only reduces the risk of environmental contamination, but also simplifies the fabrication process by eliminating the need for solvent removal steps. This, in turn, enhances the overall efficiency and cost-effectiveness of thin film production. Furthermore, physical synthesis methods also offer the advantage of achieving uniform nanoparticle distribution. The uniform dispersion of nanoparticles is crucial in many applications, the utilization of a tube furnace for the physical synthesis of silver nanoparticles presents certain limitations, including significant spatial requirements, elevated energy consumption, and extended thermal stability duration. In the realm of efficient synthesis, an alternative approach involves the utilization of a small ceramic heater that possesses a localized heating area. This particular method offers several advantages, one of which is the ability to facilitate rapid cooling of evaporated vapor. By employing such a heater, researchers can enhance the efficiency of the synthesis process without compromising the quality of the final product. The utilization of a small ceramic heater for the purpose of physical synthesis has been found to offer several advantages, including the attainment of stable particle generation characterized by high concentration and consistent temperature. The utilization of this particular methodology holds significant value in the context of conducting long-term experiments and calibrating equipment used for measuring nanoparticles. The synthesis of silver nanoparticles through laser ablation of metallic bulk materials in solution has been extensively studied and proven to be a viable method. Laser ablation involves the use of a high-energy laser to irradiate a target material submerged in a liquid medium, resulting in the generation of nanoparticles. In the case of metallic bulk materials, such as silver, the laser-induced ablation process leads to the formation of silver nanoparticles in the surrounding solution. Numerous research studies have focused on investigating the parameters that influence the synthesis of silver nanoparticles through laser ablation. These parameters include laser energy, pulse duration, repetition rate, and the composition of the liquid medium. By carefully controlling these The efficiency and characteristics of particles are contingent upon several parameters, including laser wavelength, pulse duration, ablation time, and the presence or absence of a surfactant in the liquid medium. The utilization of laser ablation technique presents a notable advantage in comparison with alternative methodologies due to its capacity to obviate the requirement for chemical reagents. The aforementioned process facilitates the generation of metal colloids that are free from impurities, thereby ensuring their purity and suitability for diverse applications (Flores-López et al. 2019).

The conventional approaches employed in the synthesis of metallic nanoparticles have demonstrated superior capabilities in terms of size regulation and reproducibility. However, these methods typically necessitate substantial energy input, involve the use of hazardous chemicals, and demand precise control over temperature and pressure conditions. Consequently, these requirements can lead to adverse environmental consequences, such as contamination, and impose additional financial burdens (Ferdous et al. 2019).

Fungi present an appealing option for the biogenic synthesis of silver nanoparticles due to their high metal tolerance and ease of handling. Additionally, they secrete significant amounts of extracellular proteins, enhancing nanoparticle stability (Du et al. 2015). Fungal cultures offer advantages over bacterial systems, showcasing robust biomass production without the need for additional filtrate extraction steps (Gade et al. 2008). Compared to plant-based synthesis, fungal mycelial mass exhibits greater resistance to agitation and pressure, making it well-suited for large-scale syntheses (Velusamy et al. 2016). Moreover, by adjusting various culture conditions such as time, temperature, pH, and biomass quantity, it is possible to influence fungal metabolism, allowing for the production of nanoparticles with desired characteristics like specific size and morphology (Zielonka and Klimek-Ochab, 2017).

The utilization of green synthesis (Fig. 2) has emerged as an alternative method for the production of silver nanoparticles. This approach involves the utilization of plant extracts or biological agents to effectively reduce silver ions and subsequently form nanoparticles. The utilization of plants as a means for synthesizing nanoparticles presents a cost-effective approach that provides an economically viable alternative for the production of nanoparticles on a large scale. In general, it has been observed that conventional physical and chemical techniques tend to be both expensive and hazardous in nature. Among the various methods available, the biological method emerges as a notable choice due to its inherent safety, simplicity, and environmentally friendly nature, coupled with its ability to yield substantial results and maintain stability (Flores-López et al. 2019). The utilization of extract derived from the Camellia sinensis plant, commonly referred to as green tea, has demonstrated effective properties as a reducing and stabilizing agent during the biosynthesis of silver nanoparticles. The utilization of plant extracts derived from Medicago sativa (commonly known as alfalfa), Cymbopogon flexuosus (lemongrass), and Pelargonium graveolens (geranium) has been explored in the synthesis of silver nanoparticles. These plant extracts have been employed as environmentally friendly reactants, thereby contributing to the development of a greener approach in the production of silver nanoparticles. In addition, it has been observed that the utilization of Datura metal leaf extract has resulted in the rapid synthesis of stable silver nanoparticles, with sizes ranging from 16 to 40 nm. This synthesis process is achieved through the introduction of silver ions, which act as a catalyst for the reaction. The leaf extract has been found to possess bio-molecules that exhibit reductant properties and serve as scaffolds for the controlled synthesis of silver nanoparticles. Table 1 demonstrates the different biological sources having the anti-diabetic activities.

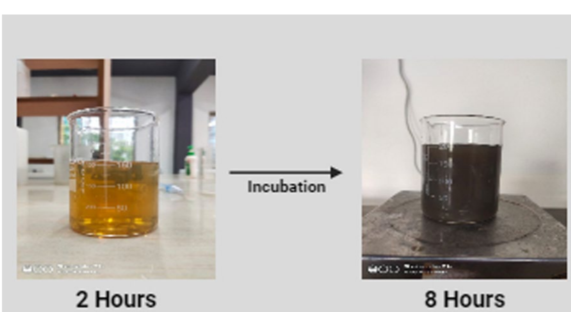

Fig. 2 Green synthesis of silver nanoparticles

In the realm of research, it is essential for researchers to carefully consider the various methods available to them, as each method possesses its own unique set of advantages and considerations (Konop et al. 2019). Consequently, researchers must exercise discernment in selecting the most appropriate method that aligns with their specific requirements and objectives.

Cytotoxicity of silver nanoparticles

The cytotoxicity of nanomaterials is subject to various influential factors, such as their dimensions, morphology, surface modifications, and the specific microorganisms targeted during testing. The present study aims to investigate the comparative toxicity of nanoparticles synthesized using green methods versus non-green methods. It is worth noting that nanoparticles synthesized using green methods have been observed to display higher levels of toxicity in comparison with those obtained through non-green methods. This observation raises important questions regarding the potential risks associated with the utilization of green synthesis approaches for nanoparticle production. By examining and comparing the toxicity profiles of nanoparticles synthesized through different methods, this research aims to contribute to the existing body of knowledge on the subject and provide valuable insights for future nanoparticle synthesis strategies. The susceptibility of certain pathogens to the cytotoxic effects of nanomaterials, specifically silver

Table 1 Anti-diabetic activity of AgNPs synthesized from biological resources

Sl. No.	Biological source of nanoparticle	Secondary metabolites of source	Parameters considered	Important finding
1	*Allium cepa*	Polyphenols, flavonoids, chlorogenic acid, quercetin, organic acids and gallic acids	α-glucosidase enzyme inhibition assay and α-amylase	Approx 74% and 60% inhibition of α-amylase ($P \leq 0.05$) and α-glucosidase ($P \geq 0.05$) respectively at 100µg/ml (Jini and Sharmila 2020)
2	*Callophylum tomentosum* (Leaves)	Saponin, alkaloids, flavonoids, phenols, tanins, glycosides	α-glucosidase, α-amylase, and DPPIV inhibition assay	Approximately 18%, 52% and 58% inhibition of α-amylase, α-glucosidase and DPPIV respectively at 500 µg/ml (Govindappa et al. 2018)
3	*Cympogon citratus* (Lemongrass)	Anthraquinones, flavonoids, phenols, tannins and alkaloids; various essential oil and deoxy sugars	α-amylase inhibition assay and GDRI (Glucose diffusion retardation index assay)	Approximately 90% inhibition of α-amylase at 100µg/ml and 81.30% inhibition of GDRI after 120 min (Govindappa et al. 2018)
4	*Justicia diffusa* (Leaves)	Alkaloids, flavonoids, coumarins and triterpenoidal glycosides	α-amylase inhibition assay	61.70% inhibition of α-amylase at 200 µg/ml concentration; 6.40% more inhibition from plant extract at the same concentration. (Anwar et al. 2018)
5	*Argyreia nervosa* (Leaves)	Sterols, carbohydrates, triterpenoids, phenols, tannins and saponins	α-amylase and α-glucosidase inhibition assay	Approximately70% inhibition of both the enzymes at 100 µg/ml. (Saratale et al. 2017)
6	*Gracillaria edulis*	Eugenol, nonane, undecane, hept-2-ene, propanediol, sulfurous acid	α-amylase inhibition assay and glucose inhibition assay	98.75% inhibition of α-amylase enzyme and 78.75% concentration of glucose decrease by diffusion at 400 µg/ml. (Abideen and Sankar 2015)
7	*Saraca asoca*	Tannins, flavonoids, and carbohydrate; proteins and amino acids	α-amylase inhibition assay	Inhibition of α-amylase with IC_{50} value of 0.35 mM (Patra et al. 2018)
8	*Avicennia officinalis*	Resins, tannins, proteins, glycosides, sterols, carbohydrates, reducing sugar and cardio glycosides; catechol	α-amylase and α-glucosidase inhibition assay	98% inhibition of α-amylase (IC_{50}-0.28 mg/ml) at 0.5 mg/ml and 9 inhibition of α-glucosidase (IC_5-0.15 mg/ml) at 0.5 mg/ml (Das et al. 2019)
9	*Syringodium isoetifolium*	Flavonoids, tannins, phenol and Vitamin C & E	α-amylase and α-glucosidase inhibition assay	77.25% inhibition of α-amylase enzyme and 45.25% concentration of glucose decrease by diffusion at 400 µg/ml. (Abideen and Sankar 2015)

nanoparticles (AgNPs), is influenced by the concurrent presence of both released Ag ions and AgNPs. The present issue has garnered attention and increased awareness regarding the potential toxicity of nanoparticles and their potential ramifications on the environment (De Brito et al. 2020). The toxicity of nanoparticles is typically greater when compared to bulk materials, resulting in adverse effects on various biological components such as cells, sub-cellular structures, and bio-molecules. The association between exposure to nanomaterials and the occurrence of oxidative stress and severe lipid peroxidation has been well-documented, with a particular emphasis on their effects on fish brain tissue. The cytotoxicity associated with silver nanoparticles (AgNPs) is widely hypothesized to arise from the production of reactive oxygen species (ROS), which subsequently leads to a decrease in glutathione levels and an elevation in ROS levels. The present study aims to investigate the effects of silver nanoparticles on animal tissues and cultured cells through in vitro studies. Previous research has demonstrated that exposure to silver nanoparticles leads to heightened levels of oxidative stress, apoptosis, and genotoxicity (Olugbodi JO et al. 2023). The effects of silver nanoparticles (AgNPs) are influenced by various factors, including their size, coatings, and the environmental conditions in which they are present. These factors contribute to the complexity of establishing direct correlations between Ag NPs and their effects. Moreover, it is imperative to thoroughly assess the stability and aging characteristics of nanoparticle samples. The prolonged storage of aged silver nanoparticles (AgNPs) in aqueous solutions has been linked to heightened toxicity, which may be attributed to the liberation of silver ions. The potential toxicity resulting from the combined exposure to silver nanoparticles (AgNPs) and silver ions has been a subject of considerable interest (Ferdous et al. 2019). However, there exists a divergence of opinions among researchers regarding the primary source of toxicity, whether it is predominantly attributed to AgNPs or the released Ag ions. In certain specialized domains, such as the realm of medical science, silver nanoparticles (AgNPs) have exhibited notable efficacy in combating a diverse range of pathogens. The efficacy of silver nanoparticles (AgNPs) derived from plant extracts in combating bacterial pathogens has been extensively investigated. Notably, AgNPs have demonstrated significant effectiveness against various bacterial strains, including Flavobacterium branchiophilum as well as both gram-positive and gram-negative bacteria. Silver nanoparticles (AgNPs) have been extensively studied due to their potential applications in various fields, including medicine. In particular, AgNPs have demonstrated cytotoxic effects against breast cancer cell lines, indicating their potential as a therapeutic agent in the treatment of breast cancer. Additionally, AgNPs have been found to possess antioxidant properties, which can help mitigate oxidative stress and prevent cellular damage. Furthermore, AgNPs exhibit antimicrobial properties. The present study provides evidence indicating that silver nanoparticles (AgNPs), particularly those derived from plant extracts, exhibit promising prospects in the field of antimicrobial and cytotoxic therapies. However, it is imperative to conduct additional investigations in order to comprehensively comprehend the underlying mechanisms of action and to establish the safety profiles of AgNPs in diverse settings (Rezvani et al. 2019).

The potential toxicity risks associated with silver nanoparticles in diabetes treatments are a subject of ongoing research, and findings may vary. While silver nanoparticles have shown promise in some studies for their antimicrobial and anti-inflammatory properties, concerns exist about their potential toxicity (Ferdous et al. 2019).

Some of the potential toxicity risks associated with silver nanoparticles

Silver nanoparticles can accumulate in various organs, raising concerns about long-term exposure and potential adverse effects on organ function. Studies have suggested that silver nanoparticles may induce cellular and genetic alterations, which could have implications for overall health. Excessive exposure to silver nanoparticles may trigger inflammatory responses in the body, potentially leading to tissue damage. Silver nanoparticles can interact with bio-molecules in the body, which may influence cellular processes and contribute to toxicity. There is emerging evidence suggesting that silver nanoparticles may affect the composition and function of gut microbiota, which plays a crucial role in overall health, including metabolic conditions like diabetes.

It is important to note that the potential toxicity of silver nanoparticles can be influenced by factors such as particle size, shape, concentration, and duration of exposure. Additionally, individual responses may vary.

Given these concerns, researchers and healthcare professionals emphasize the need for thorough toxicity assessments and well-designed clinical trials to determine the safety profile of silver nanoparticles in diabetes treatments. Before any potential application in clinical settings, a comprehensive understanding of the risks and benefits is crucial step.

Characterization

The scientific community has directed its attention toward the characterization of silver nanoparticles in order to investigate their potential anti-diabetic properties in patients (Fig. 3). The present analysis encompasses an evaluation of the efficacy, toxicity, and mechanisms of

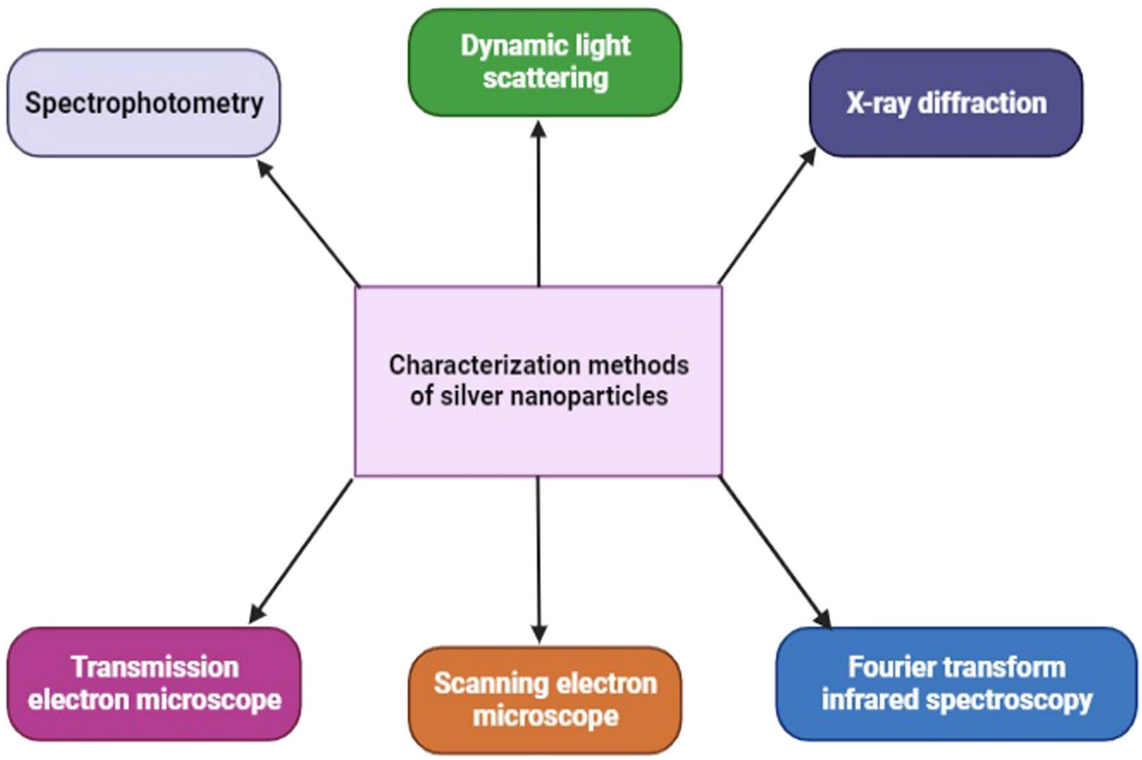

Fig. 3 Characterization techniques of silver nanoparticles

action of various characterizations in their role of combating diabetes. The comprehension of these aforementioned characteristics is crucial in the formulation and implementation of secure and efficacious therapeutic strategies for individuals diagnosed with diabetes (Wu et al. 2020).

In order to guarantee both safety and efficacy, it is imperative to conduct thorough monitoring of the physicochemical characteristics of each nanoparticle. Hence, the characterization of silver nanoparticles (AgNPs) assumes significance as it enables the assessment of the functional attributes of the synthesized particles. In order to effectively characterize silver nanoparticles (AgNPs), a range of analytical techniques have been employed (Zimkhitha et al. 2021).

UV–Vis spectroscopy

The utilization of the UV–Vis technique has been widely acknowledged as a straightforward and dependable approach for the primary characterization of nanoparticles that have been prepared. In addition to its primary applications, this technique can also be employed for the purpose of assessing the synthesis and stability of nanoparticles. The utilization of this particular technique facilitates the interaction of AgNPs with distinct wavelengths of light, thereby rendering it a convenient, dependable, sensitive, uncomplicated, efficient, and discerning method for numerous types of nanoparticles. Calibration and suspension are unnecessary for colloidal samples, as stated by previous research (Zimkhitha et al. 2021).

Fourier transform infrared spectroscopy (FTIR)

Fourier transform infrared spectroscopy (FTIR) is a highly regarded analytical technique widely employed in various scientific disciplines. This technique holds significant value due to its ability to detect even minute changes in absorbance, thereby facilitating the determination of combination bands associated with functionally dynamic residues. The methodology employed in this study is characterized by its accuracy, reproducibility, and non-invasiveness. Fourier transform infrared spectroscopy (FTIR) is a widely utilized technique in the field of nanotechnology for the authentication of functional molecules on nanoparticles, such as silver, gold, and graphene. The experimental results demonstrate a robust data set characterized by a high signal-to-noise ratio and negligible sample heat-induced effects. In general, Fourier Transform Infrared Spectroscopy (FTIR) has emerged as a straightforward, precise, and economically viable method for validating the functionality of bio-molecules.

Dynamic light scattering (DLS)

The utilization of differential light scattering (DLS) has emerged as a significant technique in the field of biological research, enabling the study of various biological activities and facilitating the evaluation of synthesized nanoparticles. The instrument possesses the capability to accurately ascertain the dimensions of particles spanning a range from sub-micron to one nanometer. The technique of dynamic light scattering (DLS) is widely employed for the determination of smaller particles. The present technique is predicated upon the intricate interplay between electromagnetic radiation and particulate matter, rendering it a frequently employed method for the determination of particle dimensions and the assessment of their dispersion characteristics. The technique of dynamic light scattering (DLS) involves the measurement of scattered light emitted by a laser beam as it passes through a colloidal suspension. By analyzing the temporal modulation of the scattered light, valuable information regarding the hydrodynamic size of particles can be obtained. The technique of dynamic light scattering (DLS) has been observed to yield more accurate size measurements in comparison with transmission electron microscopy (TEM), potentially attributable to the influence of Brownian motion. The primary application of this technique lies in the determination of particle size in aqueous solutions (Zimkhitha et al. 2021).

X-ray photoelectron spectroscopy (XPS)

X-ray photoelectron spectroscopy (XPS), alternatively referred to as electron spectroscopy for chemical analysis (ESCA), is a widely employed analytical technique utilized for the determination of empirical formulae. The utilization of high vacuum conditions has been widely employed in the field of macromolecular research for the purpose of identification and characterization of specific groups of macromolecules, such as aromatic rings. The X-ray photoelectron spectroscopy (XPS) technique is widely used to obtain comprehensive information about the surface properties of a sensor. This analytical method provides both qualitative and quantitative details, as well as specification information.

X-ray diffraction spectroscopy (XRD)

X-ray diffraction (XRD) has emerged as a highly effective method for investigating molecular and crystalline structures, as well as elucidating the dynamics of chemical species, quantifying the extent of crystallinity, and measuring particle dimensions. The utilization of this analytical technique extends to the examination of a diverse array of compounds, encompassing glasses, superconductors, inorganic catalysts, and polymers. The interaction between light and crystals leads to the formation of diffraction patterns, which serve as a reflection of the physiochemical properties inherent in the crystal's structure. When the specimen is in a powdered state, the diffracted beams emitted during analysis can yield valuable insights into the physiochemical structure of the product. X-ray diffraction (XRD) has emerged as the predominant technique for the determination and characterization of the crystalline structure of various materials. With its ability to provide detailed information about the arrangement of atoms within a crystal lattice, XRD has become the go-to method for identifying the crystalline nature of a product. By subjecting a sample to X-ray radiation and analyzing the resulting diffraction pattern, XRD enables researchers to gain insights into the crystallographic properties, such as lattice parameters, unit cell dimensions, and crystal symmetry. This non-destructive technique has found widespread applications in the technique under consideration is widely employed for multiple purposes, including phase identification, qualitative analysis, and the detection of structural imperfections. Its applications span across diverse fields such as pharmaceutical, environmental, geological, and even forensic science. One potential limitation of crystal growth is the occasional difficulty encountered during the process. In the realm of scientific research, X-ray diffraction (XRD) has emerged as an invaluable tool.

Scanning electron microscopy (SEM)

Introduction nanotechnology and nanoscience have emerged as prominent fields of study, offering immense potential for advancements in various scientific disciplines. In order to delve deeper into these domains, researchers employ a range of techniques, including electron microscopy. This paper aims to explore the utilization of scanning electron microscopy (SEM) as a valuable tool for investigating nanotechnology and nanoscience. Utilizing electron microscopy in nanotechnology and nanoscience electron microscopy has proven to be an indispensable tool in the study of nanotechnology and nanoscience. By employing a focused beam of electrons, SEM enables researchers to obtain high-resolution images of nanoscale materials and structures. This technique offers several advantages over other microscopy methods The scanning electron microscopy (SEM) technique is widely employed in various scientific disciplines to investigate the characteristics of particles, such as size, distribution, morphology, and the shapes of nanomaterials. SEM provides high-resolution surface imaging capabilities, enabling researchers to gain valuable insights into the properties and structures of these materials. By utilizing SEM, scientists can obtain detailed information about the aforementioned parameters, which is crucial for understanding the behavior and applications of particles and nanomaterials in various fields of study. The present study aims to investigate the morphology of silver powder and perform chemical composition analysis utilizing scanning electron microscopy (SEM) coupled with energy-dispersive X-ray spectroscopy (EDX). By employing SEM, a comprehensive examination of the surface characteristics and structure of the silver powder will be conducted. Additionally, the EDX technique will be employed to determine the elemental composition of the silver powder. This research endeavor seeks to provide valuable insights into the physical and chemical properties of silver powder, contributing to a deeper understanding of its potential applications in various fields. Nanomaterials have emerged as a significant area of study in recent years, offering great potential for various applications (Zimkhitha et al. 2021). Among the various tools available for comprehending the unique properties and behaviors of nanomaterials, one stands out as particularly powerful. This tool, which has garnered considerable attention from researchers, holds the promise of unlocking a deeper understanding of nanomaterials.

Atomic force microscopy (AFM)

Atomic force microscopy (AFM) has emerged as a widely utilized technique for investigating the dispersion and aggregation behavior of nanomaterials. The application of AFM in this context has garnered significant attention due to its ability to provide high-resolution imaging and characterization at the nanoscale. This paper aims to explore the prevalent use of AFM in the study of nanomaterial dispersion and aggregation, highlighting its advantages and limitations in this research domain. By examining existing literature and experimental findings, a comprehensive understanding of AFM's role in elucidating the device provides users with three distinct scanning modes: contact, non-contact, and intermittent sample contact. Atomic force microscopy (AFM) has emerged as a valuable tool in the field of nanotechnology, particularly for investigating the intricate interplay between nanomaterials and lipid bilayers. This capability sets AFM apart from electron microscopy techniques, which are unable to provide comparable insights into this specific area of study. One potential limitation of utilizing a cantilever in measurements is the possibility of overestimating lateral dimensions due to the size of the cantilever. To mitigate this issue, it is crucial to exercise caution and implement strategies to minimize errors (Zimkhitha et al. 2021).

Transmission electron microscopy (TEM)

The transmission electron microscope (TEM) is widely recognized as a pivotal technique in the field of particle characterization. Its ability to provide high-resolution imaging and detailed structural information has made it an indispensable tool in various scientific disciplines. This paper aims to highlight the significance of TEM in particle characterization and its contributions to advancing our understanding of particle properties. TEM operates on the principle of transmitting a beam of electrons. The utilization of particle analysis techniques enables the determination of various characteristics of particles, including their quantitative size, distribution, and morphology. The determination of magnification in transmission electron microscopy (TEM) is contingent upon two key factors: the separation between the objective lens and the specimen, and the separation between the objective lens and the image plane. These parameters play a crucial role in the overall magnification achieved in TEM imaging. In the realm of electron microscopy, the comparison between scanning electron microscopy (SEM) and transmission electron microscopy (TEM) has been a subject of considerable interest. This discourse aims to elucidate the disparities between these two techniques in terms of resolution and analytical capabilities. Firstly, it is widely acknowledged that TEM surpasses SEM in terms of resolution. The fundamental principle underlying TEM involves the transmission of a beam of electrons through a thin specimen the scanning electron microscope (SEM) is a widely used tool in various scientific fields due to its ability to provide high-resolution images of samples. However, it is important to acknowledge that SEM does have certain limitations that should be taken into consideration. One such limitation is the requirement for a high vacuum environment during imaging. This is necessary to prevent the scattering of electrons by gas molecules, which can interfere with the quality of the image obtained. Additionally, SEM requires samples to be prepared as thin sections to achieve optimal results. This can be a time-consuming process, as it involves carefully cutting and preparing the sample to meet the necessary specifications (Zimkhitha et al. 2021). Researchers must be aware of these limitations when utilizing SEM in their studies, as they can impact the overall effectiveness and efficiency of the imaging process.

Research progress in silver nanoparticles to treat diabetes mellitus

Research by Khan et al. (2023) investigated the molecular mechanisms underlying the anti-diabetic effects of silver nanoparticles. The study demonstrated that these nanoparticles modulate key signaling pathways involved in insulin signaling, oxidative stress and inflammation, providing a comprehensive understanding of their mode of action. Silver nanoparticles have been incorporated into drug delivery systems to enhance the bio-availability of anti-diabetic drugs. Research by Wahab Et Al. (2022) discussed the development of silver nanoparticle-based carriers for targeted delivery of insulin and other therapeutic agents, offering a promising approach to improve treatment outcomes. The antioxidant properties of silver nanoparticles were explored in a study by Bold et al. (2022). The nanoparticles were shown to reduce oxidative stress markers in diabetic subjects, highlighting their potential in mitigating the oxidative damage associated with diabetes mellitus. A study by Wang et al. (2020) focused on the protective effects of silver nanoparticles on pancreatic beta cells. The findings suggested that silver nanoparticles exerted a cytoprotective effect on beta cells, preserving their function and integrity in the face of diabetic challenges. Inflammation is a key contributor to diabetes complications, and silver nanoparticles were investigated for their anti-inflammatory effects in a study by Ferdous and Nemmar (2020). The nanoparticles were found to suppress inflammatory markers, suggesting a potential role in managing chronic low-grade inflammation in diabetes. A study by Alkhalaf et al. (2020), focused on the potential therapeutic effects of silver nanoparticles synthesized with Calligonum comosum extract in diabetic nephropathy. The researchers explore the anti-inflammatory and antioxidant properties of the nanoparticles. In a study by Alkaladi et al. (2014), silver nanoparticles were found to enhance insulin sensitivity in diabetic animal models. The nanoparticles demonstrated a positive impact on glucose uptake and utilization, leading to improved glycemic control. The potential anti-diabetic effects of silver nanoparticles synthesized from Aloe vera extract. Al-Attar et al. (2019) explored the changes in blood glucose levels, insulin sensitivity and oxidative markers in diabetic rats. In a study by M. Hajipour et al. investigated the impact of silver nanoparticles on glucose uptake by examining their effect on glucose transporter 4 (GLUT4) expression. Enhances glucose uptake could be relevant to diabetes management.

The future of silver nanoparticles (AgNPs) in anti-diabetic activity

Future research may focus on tailoring silver nanoparticles for specific patient profiles, considering genetic variations and individual responses. Precision medicine could enhance the efficacy and minimize side effects in diabetic patients. Investigating combination therapies involving silver nanoparticles and existing anti-diabetic drugs could be a key area of exploration. Synergistic effects may lead to enhanced therapeutic outcomes and improved management of diabetes (Ayech et al. 2020). Researchers may continue to advance the design of silver nanoparticles as drug delivery systems. Developing nanocarriers for targeted and controlled drug release could improve the bio-availability of anti-diabetic drugs and reduce systemic side effects. Utilizing bioinformatics and computational modelling can help predict the interactions between silver nanoparticles and biological systems. This approach can accelerate the identification of potential anti-diabetic mechanisms and optimize nanoparticle design. The future may witness an increased focus on translating preclinical findings into clinical applications. Conducting well-designed human clinical trials will be crucial for establishing the safety and efficacy of silver nanoparticles in treating diabetes. Researchers will likely work on enhancing the bio-compatibility of silver nanoparticles to ensure their safety for therapeutic use. Surface modifications and engineering techniques may be explored to minimize potential toxicity. As silver nanoparticles move toward clinical applications, long-term safety studies will be essential. Understanding the potential cumulative effects and any chronic toxicity is crucial for ensuring the sustained well-being of patients. Achieving regulatory approval for the use of silver nanoparticles in anti-diabetic therapies requires standardized protocols, rigorous testing, and adherence to regulatory guidelines. Establishing a robust framework for nanoparticle-based therapies is vital for their widespread acceptance. The future of silver nanoparticles in anti-diabetic research will likely involve increased collaboration between nanotechnologists, biologists, clinicians, and other experts. Interdisciplinary efforts can provide comprehensive insights and foster innovation. As with any emerging technology, ethical considerations surrounding the use of silver nanoparticles must be addressed. Societal acceptance, awareness, and responsible development are critical aspects that researchers and policymakers should consider. Researchers will likely explore methods to mitigate the environmental impact of silver nanoparticle production and usage. Sustainable and eco-friendly approaches to nanoparticle synthesis may become a focus of future investigations (Shanmuganathan et al. 2019).

Conclusion

Silver, a versatile element, exists in various forms including Ag0, Ag2+, and Ag3+, with elemental silver demonstrating exceptional electrical, optical, and thermal conductivity, as well as low contact resistance. Diabetes Mellitus, characterized by insulin resistance or ineffective insulin action, increases susceptibility to vascular disease, particularly thrombosis. Platelets in type 2 diabetes patients are more reactive due to factors like hyperglycemia and hyperlipidemia. Anti-platelet therapy is recommended for diabetic patients with a high cardiovascular risk. Silver nanoparticles have shown potential in inhibiting thrombin-induced platelet aggregation, reducing aggregation by approximately 50% in non-insulin-dependent diabetes mellitus (NIDDM) patients. Nanobiotechnology, particularly nanomedicine, offers promising solutions for diabetes management by improving drug delivery and release. Nanoparticles have various applications in diabetes, including glucose monitoring, biosensing, imaging, and insulin delivery. Plant-mediated silver nanoparticles show potential in mitigating oxidative stress and inhibiting alpha-amylase, offering cost-effective, safe, and therapeutic benefits.

Abbreviations

AgNPs	Silver nanoparticles
T2DM	Type 2 Diabetes Mellitus
PEPCK	Phosphoenolpyruvate carboxykinase
AI	Artificial Intelligence
AMPK	AMP-activated protein kinase
PPARs	Peroxisome proliferator-activated receptors
NaBH4	Sodium borohydride
ROS	Reactive oxygen species
FTIR	Fourier Transform Infrared Spectroscopy
DLS	Dynamic Light Scattering
XPS	X-ray Photoelectron Spectroscopy
ESCA	Electron Spectroscopy for Chemical Analysis
XRD	X-ray Diffraction Spectroscopy
SEM	Scanning Electron Microscopy
EDX	X-ray Spectroscopy
AFM	Atomic Force Microscopy
TEM	Transmission Electron Microscopy
NIDDM	Non-insulin-dependent diabetes mellitus
T1DM	Type 1 Diabetes Mellitus

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Author contributions
We declare that the work was done by the authors named in this article: SP, IS, NS, AB, AC, SM, and MC. IS, SP, and AB collected the data from previous findings, and AC, MC, and SM drafted the final manuscript. NS supervised the manuscript. All authors have read and approved the final manuscript.

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Declarations

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Consent for publication
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Competing interests
No, the authors declare that they have no competing interests.

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