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Biogenic Nanoparticles from Edible Plants: Integrative Therapeutics for Obesity, Diabetes, and Cancer

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ABSTRACT

Biogenic nanoparticles (BNPs), derived from edible plant extracts, represent an eco-friendly, cost-effective, and sustainable alternative to conventional nanomaterials. Rich in bioactive phytochemicals, edible plants serve as efficient platforms for the green synthesis of BNPs with diverse biomedical applications. Recent studies demonstrate that these plant-based nanoparticles exhibit potent antioxidant, anti-inflammatory, antidiabetic, anti-obesity, and anticancer activities. These therapeutic properties are largely attributed to their ability to regulate molecular signaling pathways, enhance drug bioavailability, and selectively target pathological tissues. This review highlights the synthesis, characterization, and biomedical potential of edible plant-derived BNPs, with a focus on their application in managing obesity, diabetes, and cancer. It also discusses mechanistic insights, current challenges, and future directions in clinical translation.

Keywords: Biogenic nanoparticles, Edible plants, Antioxidant, Diabetes, Cancer

INTRODUCTION

Nanotechnology has ushered in a new era of possibilities in biomedical research, especially in the realms of disease diagnosis, targeted drug delivery, and therapeutic intervention[1, 2]. One of the most promising branches of nanotechnology is the development of biogenic nanoparticles (BNPs), which are nanoparticles synthesized using biological entities such as plants, fungi, bacteria, or algae[3–5]. Among these, plant-mediated synthesis stands out for being environmentally sustainable, economically viable, and suitable for large-scale production. Edible plants, in particular, offer a safe and effective platform for BNP synthesis due to their abundant phytochemical repertoire and intrinsic compatibility with the human body[6].

Biogenic nanoparticles from edible plants are unique because their surface is often decorated or capped with naturally occurring bioactive compounds such as polyphenols, flavonoids, terpenoids, alkaloids, and other secondary metabolites[7, 8]. These molecules not only assist in nanoparticle formation by reducing metal ions but also endow the nanoparticles with enhanced biological functionalities. As a result, BNPs synthesized from edible plants exhibit superior biocompatibility, reduced toxicity, and improved therapeutic efficacy compared to conventionally synthesized nanoparticles[7, 9]. This dual functionality such as structural stability and biological activity makes edible plant-derived BNPs a powerful tool in integrative medicine.

The global burden of non-communicable diseases like obesity, diabetes mellitus, and cancer continues to rise, accounting for significant morbidity and mortality worldwide[10–12]. These diseases, although distinct in clinical manifestations, share common pathophysiological threads such as chronic inflammation, oxidative stress, insulin resistance, and metabolic dysregulation. Traditional pharmacological approaches often target singular pathways and may cause adverse side effects over prolonged use. Hence, there is a growing demand for multi-targeted, safe, and effective treatment strategies.

In this context, BNPs synthesized from edible plants represent a holistic and promising therapeutic strategy. By leveraging the synergistic effects of nanoscale materials and plant-derived bioactives, these BNPs have shown potential in modulating inflammatory pathways, enhancing antioxidant defenses, improving glucose metabolism, and inducing selective cytotoxicity in cancer cells. Furthermore, the biodegradable nature of these nanoparticles and their capacity for site-specific drug delivery can minimize systemic toxicity and improve patient compliance[3, 13, 14]. Recent studies have reported that BNPs can improve the bioavailability of poorly soluble phytochemicals, such as curcumin and quercetin, which are often limited in clinical use due to poor pharmacokinetics[15]. These nanoparticles can traverse biological barriers more efficiently, target diseased tissues more precisely, and release their cargo in a controlled manner, thereby amplifying therapeutic outcomes.

Moreover, their synthesis does not require high temperatures, harsh chemicals, or sophisticated infrastructure, making them ideal for use in resource-limited settings and scalable production[15]. This review aims to explore the emerging applications of BNPs derived from edible plants in the integrative management of obesity, diabetes, and cancer. It will delve into the mechanisms of green synthesis, catalog commonly used edible plants for nanoparticle production, and highlight preclinical and clinical studies demonstrating their efficacy. Through this lens, the review underscores the potential of green nanotechnology as a transformative tool for managing complex metabolic and oncological disorders.

Green Synthesis of Nanoparticles Using Edible Plants

Green synthesis refers to the eco-friendly and biologically safe production of nanoparticles using natural resources[16]. Unlike conventional physical or chemical methods that involve toxic solvents, high temperatures, and costly equipment, green synthesis utilizes the reducing and stabilizing properties of biomolecules found in plants to produce nanoparticles under mild conditions[3, 16]. Among various biological systems, edible plants have gained considerable attention due to their phytochemical richness, safety profile, and widespread availability.

Mechanism of Synthesis

The core mechanism of green synthesis involves the reduction of metal salt precursors, such as silver nitrate ($AgNO_3$) or chloroauric acid ($HAuCl_4$), by plant-derived phytochemicals[17]. Compounds such as flavonoids, terpenoids, alkaloids, saponins, phenolic acids, and tannins play a dual role as both reducing agents facilitating the conversion of metal ions to metal atoms—and capping agents that stabilize the nanoparticle surface. These bioactives contain functional groups like hydroxyl (-OH), carboxyl (-COOH), and amine ($-NH_2$) that interact with metal ions to initiate nucleation and growth of nanoparticles[18]. The synthesis process typically begins with the preparation of a plant extract, obtained by boiling or soaking plant material (leaves, roots, seeds, or fruits) in water or alcohol[3, 19]. The extract is then mixed with a solution of metal salt, where reduction reactions occur spontaneously, often indicated by a color change in the mixture (e.g., pale yellow to brown for silver nanoparticles). This visually observable change signifies the formation of nanoparticles, which can then be purified, characterized, and tested for biological activity[3]. The characteristics of the resulting nanoparticles such as size, shape, crystallinity, and surface charge are influenced by factors including pH, temperature, concentration of reactants, and duration of synthesis. Importantly, these parameters can be fine-tuned to optimize nanoparticle properties for specific biomedical applications[20].

Commonly Used Edible Plants

Numerous edible plants have been successfully employed for BNP synthesis, each contributing unique phytochemicals that influence nanoparticle properties and biological efficacy:

Curcuma longa (Turmeric): Turmeric is rich in curcumin, a polyphenolic compound known for its anti-inflammatory, antioxidant, and anticancer properties. Curcumin acts as a reducing agent in nanoparticle synthesis and enhances the therapeutic functionality of the resulting BNPs, particularly in targeting inflammation and cancer[21].

Camellia sinensis (Green Tea): Green tea contains high levels of catechins and other polyphenols, which have strong reduced capacities. Nanoparticles synthesized using green tea extracts exhibit potent antioxidant and antimicrobial activities, making them suitable for treating infections and metabolic disorders[22].

Allium sativum (Garlic): Garlic is abundant in organosulfur compounds such as allicin and ajoene, which impart significant antimicrobial, antidiabetic, and anti-inflammatory effects. These compounds contribute to both the formation and therapeutic activity of BNPs, especially in diabetes and cardiovascular diseases[23].

Zingiber officinale (Ginger): Known for its bioactive gingerols and shogaols, ginger has demonstrated powerful antioxidant and anticancer properties. BNPs synthesized with ginger extract have shown promising results in cancer cell inhibition and metabolic regulation[24].

Moringa oleifera: Often labeled a "superfood," Moringa is packed with vitamins, flavonoids, and phenolics. It has shown hypoglycemic, antihypertensive, and anticancer effects. Moringa-mediated nanoparticles have been studied for their role in blood sugar control, oxidative stress reduction, and tumor inhibition[25]. Edible plant-mediated green synthesis of nanoparticles is a versatile, sustainable, and therapeutically valuable approach. The ability to produce bioactive, safe, and functional nanoparticles from common dietary plants opens new avenues for managing obesity, diabetes, and cancer through integrative and personalized medicine[25].

Characterization Techniques

In the synthesis and study of nanomaterials or nanoparticles, thorough characterization is crucial to confirm their structural, morphological, and physicochemical properties[26]. A combination of analytical techniques is employed to assess parameters such as particle size, morphology, crystallinity, elemental composition, surface functional groups, and stability. The following are key characterization tools commonly used:

UV-Visible Spectroscopy (UV-Vis): UV-Vis spectroscopy is a fundamental and non-destructive technique used to monitor the optical properties of nanoparticles, particularly during synthesis. It works on the principle of absorption of ultraviolet or visible light by the sample, resulting in electronic transitions**[27]**. This method is especially useful in confirming the formation of metallic nanoparticles like gold or silver, which exhibit surface plasmon resonance (SPR) a distinct absorption peak typically ranging between 400–500 nm depending on the size and shape of the nanoparticles. UV-Vis spectroscopy can be used to monitor reaction kinetics, determine the concentration of nanoparticles, and assess their stability over time. Shifts in the SPR peak can also indicate particle aggregation or changes in dielectric properties[**27**].

Transmission Electron Microscopy (TEM): TEM is a high-resolution imaging technique that allows for the direct visualization of nanoparticles at the nanometer to sub-nanometer scale. By passing an electron beam through an ultrathin specimen, TEM provides detailed information about the internal structure, size distribution, shape, and crystalline nature of individual nanoparticles[**28**]. It can resolve features below 1 nm, making it ideal for assessing monodispersity and morphology. Furthermore, selected area electron diffraction (SAED) patterns obtained during TEM analysis can offer insight into the crystalline nature of nanoparticles[**28**]. TEM is indispensable in validating size measurements provided by other techniques and in identifying structural defects and interfaces at atomic resolution[**28**].

Scanning Electron Microscopy (SEM): SEM is used to examine the surface morphology and topography of nanoparticles and nanocomposites. Unlike TEM, which transmits electrons through the sample, SEM scans the surface with a focused beam of electrons, producing high-resolution images by detecting secondary or backscattered electrons[**29**]. This allows for the three-dimensional visualization of surface structures, particle agglomeration, and textural features. SEM is particularly useful when analyzing powdered or solid-state nanomaterials.[**29**] Coupled with Energy Dispersive X-ray Spectroscopy (EDS or EDX), SEM can also provide semi-quantitative elemental analysis, giving insights into the composition and distribution of elements across the sample surface.

X-ray Diffraction (XRD): XRD is employed to determine the crystalline structure, phase purity, and average crystallite size of nanoparticles[**30**]. It is based on the constructive interference of monochromatic X-rays and the crystal lattice of a material, described by Bragg's Law. Each material has a characteristic XRD pattern, enabling the identification of different crystalline phases. In the context of nanomaterials, the broadening of XRD peaks can be analyzed using the Scherrer equation to estimate crystallite size[**31**]. XRD is also effective in determining lattice parameters, crystal symmetry, and the degree of crystallinity, making it an essential tool for understanding the internal structural arrangement of nanoparticles.

Fourier Transform Infrared Spectroscopy (FTIR): FTIR spectroscopy is a valuable tool for identifying functional groups and molecular interactions present on the surface of nanoparticles[**32**]. It measures the absorbance of infrared radiation by the sample, which corresponds to the vibrational transitions of chemical bonds. FTIR is especially useful in confirming the presence of capping or stabilizing agents, such as polymers, surfactants, or biomolecules, which often functionalize nanoparticle surfaces. Characteristic absorption bands in the FTIR spectrum can reveal the presence of hydroxyl, carboxyl, amine, or other functional groups.[**32**] This information is critical in understanding nanoparticle surface chemistry, biocompatibility, and potential reactivity.

Dynamic Light Scattering (DLS): DLS is widely used to determine the hydrodynamic size and polydispersity index (PDI) of nanoparticles dispersed in a liquid medium[**33**]. It analyzes the fluctuations in the intensity of light scattered by particles undergoing Brownian motion. The technique provides an average particle diameter, including any surface-bound molecules or hydration layers, making it typically larger than the core size measured by TEM or SEM. DLS also gives insight into colloidal stability a lower PDI indicates a more uniform particle size distribution[**33**]. Additionally, DLS measurements often include zeta potential analysis, which quantifies surface charge and predicts the stability of nanoparticle suspensions; higher absolute values of zeta potential suggest better stability due to electrostatic repulsion between particles.

Therapeutic Applications

Anti-Obesity Effects: Obesity, marked by excessive lipid accumulation, insulin resistance, and chronic low-grade inflammation, can be effectively targeted by biogenic nanoparticles (BNPs)[34, 35]. These nanoparticles regulate adipogenesis by downregulating key transcription factors like PPAR-γ and C/EBPα, thereby inhibiting adipocyte differentiation[36]. Additionally, certain BNPs influence central appetite regulation mechanisms, leading to reduced food intake. They also modulate lipid metabolism by promoting lipolysis and enhancing fatty acid oxidation, contributing to the reduction of body fat. For instance, silver nanoparticles synthesized from *Moringa oleifera* significantly reduced body weight and serum lipid levels in obese rat models, demonstrating their therapeutic potential. Through these multifaceted mechanisms, BNPs offer a promising approach to controlling obesity with potentially fewer side effects than conventional therapies[37].

Antidiabetic Effects: Biogenic nanoparticles (BNPs) exhibit significant antidiabetic properties by targeting key aspects of glucose metabolism and insulin function. They protect pancreatic β-cells from oxidative damage, preserving insulin production[38]. BNPs also inhibit carbohydrate-digesting enzymes such as α-amylase and α-glucosidase, thereby reducing postprandial glucose spikes. Furthermore, they enhance insulin signaling pathways by improving insulin receptor sensitivity and promoting GLUT4 translocation, facilitating efficient glucose uptake by cells[38]. These actions are complemented by BNPs' ability to reduce oxidative stress and inflammation, common contributors to insulin resistance. A notable example is gold nanoparticles synthesized from *Cinnamon zeylanicum*, which improved fasting blood glucose and insulin levels in diabetic animal models, underscoring their efficacy in glycemic control[38]. Collectively, BNPs present a natural and potentially safer alternative for managing diabetes.

Anticancer Effects: Biogenic nanoparticles (BNPs) demonstrate potent anticancer activity through multiple cellular and molecular mechanisms[3, 39]. They induce apoptosis in cancer cells by generating reactive oxygen species (ROS), which leads to mitochondrial dysfunction and caspase activation. BNPs also promote DNA fragmentation and arrest the cell cycle, thereby halting cancer cell proliferation. Additionally, they inhibit angiogenesis and metastasis, effectively suppressing tumor growth and spread. BNPs are particularly valuable in targeted drug delivery, as they can be engineered to selectively accumulate in tumor tissues, minimizing off-target toxicity[39]. For example, BNPs derived from *Camellia sinensis* induced apoptosis in MCF-7 breast cancer cells by activating caspase-3 and downregulating the anti-apoptotic protein Bcl-2[40]. These findings highlight BNPs as a versatile and promising tool in cancer therapy, offering targeted action with reduced systemic side effects.

Mechanistic Insights

Oxidative Stress Modulation: Biosynthesized nanoparticles (BNPs) help mitigate oxidative stress by scavenging reactive oxygen species (ROS), which are harmful byproducts of cellular metabolism[41–43]. These nanoparticles reduce lipid peroxidation, a damaging process to cell membranes, and enhance the activity of endogenous antioxidant enzymes. Key antioxidants influenced by BNPs include superoxide dismutase (SOD), catalase (CAT), and glutathione (GSH). By upregulating these defenses[44], BNPs help maintain redox balance, protect cells from oxidative damage, and prevent the progression of oxidative stress-related diseases such as cancer, diabetes, and neurodegeneration. This makes them promising agents in antioxidant therapy.

Inflammatory Pathway Inhibition: BNPs exhibit anti-inflammatory effects by modulating key inflammatory mediators and pathways. They suppress the release of pro-inflammatory cytokines, including tumor necrosis factor-alpha (TNF-α), interleukin-6 (IL-6), and interleukin-1 beta (IL-1β), which play crucial roles in chronic inflammation[45]. Furthermore, BNPs inhibit the nuclear factor-kappa B (NF-κB) and mitogen-activated protein kinase (MAPK) signaling pathways, both of which are central regulators of the inflammatory response[46]. By downregulating these pathways, BNPs reduce inflammation and tissue damage, offering therapeutic potential in conditions such as arthritis, cardiovascular disease, and cancer where inflammation plays a critical role[46].

Metabolic Pathway Regulation: BNPs influence several metabolic signaling pathways, including AMP-activated protein kinase (AMPK), phosphoinositide 3-kinase/protein kinase B (PI3K/Akt), and the mammalian target of rapamycin (mTOR)[47]. These pathways are fundamental to energy metabolism, cell growth, insulin signaling, and cancer progression. Through modulation of AMPK, BNPs can enhance glucose uptake and fatty acid oxidation. Their regulation of PI3K/Akt and mTOR pathways helps control cell proliferation, survival, and autophagy[47]. These multifaceted interactions position BNPs as valuable tools in managing metabolic disorders such as obesity, diabetes, and cancer, where dysregulation of these pathways is common.

Epigenetic and Genetic Modulation: BNPs have shown potential to modulate gene and epigenetic expression, influencing key biological processes[48]. They can alter the expression of genes involved in apoptosis, cell proliferation, glucose metabolism, and lipid homeostasis. Additionally, BNPs may affect DNA methylation, histone modification, and non-coding RNAs, thereby impacting epigenetic regulation[48]. These modifications can influence disease outcomes and treatment responses[48]. The ability of BNPs to target specific gene networks provides a promising avenue for personalized medicine, especially in cancer therapy and metabolic disease management, where gene expression patterns play a crucial role in disease development and progression.

Advantages of Plant-Based BNPs

Plant-based BNPs offer several significant advantages. They are biocompatible and generally exhibit lower toxicity than chemically synthesized nanoparticles, making them safer for biomedical applications[49, 50]. The use of plants provides a cost-effective and scalable production platform. Moreover, these nanoparticles demonstrate multifunctional therapeutic properties, including antioxidant, anti-inflammatory, antimicrobial, and anticancer activities[49]. The biosynthesis process is sustainable and environmentally friendly, avoiding the use of harmful chemicals. Additionally, plant extracts act as natural reducing and capping agents, eliminating the need for synthetic stabilizers[49, 51]. These features collectively make plant-based BNPs attractive candidates for future pharmaceutical and therapeutic applications.

Challenges and Limitations

Despite their potential, plant-based BNPs face several challenges. One major limitation is batch-to-batch variability, which can affect nanoparticle size, shape, and biological properties, thereby impacting reproducibility and clinical outcomes. Scaling up production for industrial use remains difficult due to inconsistent synthesis methods and limited standardization. Furthermore, there is an incomplete understanding of the pharmacokinetics, biodistribution, and long-term behavior of BNPs in vivo. Regulatory frameworks for clinical approval are still evolving, posing additional barriers to their translation into approved therapies. Lastly, concerns about potential toxicity at high doses or with prolonged exposure must be thoroughly addressed through detailed toxicological assessments.

Future Perspectives

The future of plant-based BNPs lies in overcoming current limitations and enhancing their therapeutic utility. Standardizing synthesis protocols and characterization techniques is essential for ensuring reproducibility and scalability. In vivo validation through robust preclinical and clinical studies will help establish safety and efficacy. Advanced delivery strategies, such as ligand-based targeting, can improve the specificity and bioavailability of BNPs. Integrating artificial intelligence (AI) and machine learning into nanoparticle design can accelerate discovery and optimization processes. Additionally, developing nanoformulations that allow the co-delivery of phytochemicals and conventional drugs could enhance therapeutic outcomes and reduce side effects in complex diseases.

CONCLUSION

Biogenic nanoparticles synthesized from edible plants offer a promising avenue in the integrative treatment of obesity, diabetes, and cancer. Their inherent bioactivity, coupled with the advantages of nanotechnology, enables them to modulate complex disease pathways with precision. Despite current challenges, ongoing research and technological advances are poised to usher in a new era of green nanomedicine in chronic disease management.

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