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Review Article

Green Synthesis of Prunus Dulcis (Almond Gum) Capped Silver Nanoparticles Enhancing In Vivo Wound Healing Potential: Comprehensive Review

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Abstract

The rising demand for sustainable and biocompatible materials in biomedical applications has led to significant interest in green-synthesized nanoparticles. This review explores the green synthesis of silver nanoparticles (AgNPs) using *Prunus dulcis* (almond gum) as a natural capping and stabilizing agent, with a focus on their potential to enhance in vivo wound healing. Almond gum, a natural biopolymer, offers numerous benefits, including biodegradability, water solubility, and bioactivity, which improve the stability and biocompatibility of AgNPs while reducing environmental impact. The unique properties of almond gum-capped AgNPs, such as enhanced antimicrobial efficacy, anti-inflammatory effects, and antioxidant activity, make them particularly advantageous for wound healing applications. We analyze the mechanisms through which AgNPs promote wound repair, including bacterial inhibition, collagen synthesis, and angiogenesis, while mitigating oxidative stress and inflammation. Furthermore, in vivo studies demonstrate accelerated wound closure, reduced infection, and minimized inflammation, underscoring the clinical potential of these biogenic nanoparticles. This review also addresses current challenges, such as production scalability, nanoparticle consistency, and the need for comprehensive toxicity studies to optimize AgNPs for medical use. The findings indicate that almond gum-capped AgNPs represent a promising, eco-friendly alternative for wound care, contributing to advances in regenerative medicine through sustainable nanotechnology.

Keywords: Green synthesis, Silver nanoparticles, Almond gum, Wound healing, Biocompatible materials.

INTRODUCTION

Nanotechnology has transformed the biomedical field with its potential applications in diagnostics, therapeutics, and regenerative medicine (Bhattacharya *et al*., 2020). Among these applications, silver nanoparticles (AgNPs) have garnered significant attention due to their antimicrobial, anti-inflammatory, and wound-healing properties (Yin *et al*., 2021). AgNPs exhibit a broad spectrum of antimicrobial activity, effectively targeting bacterial, viral, and fungal pathogens, making them ideal candidates for wound care (Kim *et al*., 2022). However, the synthesis of AgNPs often involves toxic chemicals, which present environmental and health hazards (Siddiqi *et al*., 2018). Green synthesis, a sustainable and eco-friendly approach, has emerged as an alternative, utilizing plant extracts and natural biopolymers to produce nanoparticles without harmful by-products (Ahmed *et al*., 2016). Prunus dulcis, commonly known as almond, is a source of natural gum that offers unique properties as a stabilizing and capping agent for nanoparticles. Almond gum has high biocompatibility, natural polysaccharide content, and stabilizing abilities, which make it an excellent medium for nanoparticle synthesis (Bajpai *et al*., 2019). Recent research has focused on utilizing almond gum in the synthesis of AgNPs due to its ability to enhance the stability and biocompatibility of these particles, which are essential for biomedical applications (Singh & Sharma, 2021). Additionally, the biocompatibility of Prunus dulcis gum enhances the therapeutic applicability of AgNPs, particularly in wound healing, where non-toxic, biodegradable materials are essential (Kumar *et al*., 2020).

The use of green-synthesized AgNPs in wound healing is driven by the particles' multi-faceted properties, including their antimicrobial activity and ability to promote cell proliferation and tissue regeneration (Alavi & Rai, 2019). These nanoparticles interact with bacterial cell membranes, leading to oxidative stress and cell lysis, which is particularly beneficial in preventing infections in open wounds (Sharma *et al*., 2020). In addition to antimicrobial effects, AgNPs have been shown to stimulate fibroblast proliferation, collagen deposition, and angiogenesis, all crucial steps in the wound-healing cascade (Khorrami *et al*., 2019). The biocompatible capping of AgNPs with almond gum further enhances these effects, as it not only stabilizes the nanoparticles but also minimizes potential cytotoxic effects, making them safer for vivo applications (Rahman *et al*., 2021).

Given the need for eco-friendly and effective wound healing agents, green synthesis of AgNPs using almond gum represents a promising avenue for research. This review aims to explore the methods of synthesizing Prunus dulcis-capped silver nanoparticles and evaluate their effectiveness in wound healing applications. We will also examine the challenges and future potential of utilizing plant-based materials in nanotechnology, with a focus on almond gum as a biocompatible, sustainable capping agent.

Role of Silver Nanoparticles in Wound Healing

Silver nanoparticles (AgNPs) have been extensively studied for their therapeutic applications, particularly in wound healing. The unique physicochemical properties of AgNPs, such as their large surface area and high reactivity, enable them to act as effective antimicrobial agents. These nanoparticles can disrupt bacterial cell membranes, leading to cellular lysis and subsequent cell death, thus preventing infection in wounds (Rajeshkumar *et al*., 2018). The antimicrobial properties of AgNPs are crucial, as infections are one of the primary complications in wound management, often leading to delayed healing and increased risk of complications (Panáček *et al*., 2017). In addition to their antimicrobial properties, AgNPs possess anti-inflammatory properties, which further aid in wound healing. AgNPs have been shown to reduce inflammatory cytokine expression, leading to a more favorable healing environment (Ahmad *et al*., 2020). This reduction in inflammation promotes faster wound closure and minimizes scarring, as demonstrated by studies showing that AgNP-treated wounds exhibit enhanced re-epithelialization and tissue regeneration (Martinez-Gutierrez *et al*., 2013). Additionally, AgNPs encourage the formation of granulation tissue and promote collagen deposition, both essential steps in the wound healing process (Paladini & Pollini, 2019).

Furthermore, AgNPs contribute to angiogenesis, or the formation of new blood vessels, which is a vital part of the wound-healing cascade (Gurunathan *et al*., 2014). Angiogenesis facilitates oxygen and nutrient supply to the healing tissue, supporting cell proliferation and tissue repair. The pro-angiogenic properties of AgNPs have been supported by in vitro and in vivo studies, which show enhanced endothelial cell migration and proliferation in the presence of AgNPs (González *et al*., 2016). Overall, the multifunctional properties of AgNPs make them promising agents in wound healing applications.

Biological Activity of Prunus dulcis (Almond Gum) Capped AgNPs

The use of Prunus dulcis (almond gum) as a capping agent for AgNPs enhances the biocompatibility and therapeutic potential of the nanoparticles. Almond gum, a natural biopolymer, offers various benefits as a stabilizing agent, such as high water solubility, biodegradability, and non-toxicity, which are advantageous for biomedical applications (Bajpai *et al*., 2019). The capping of AgNPs with almond gum results in a biologically active coating that not only stabilizes the nanoparticles but also adds synergistic effects that enhance their wound-healing potential (Gopalakrishnan *et al*., 2021). Almond gum-capped AgNPs demonstrate enhanced antimicrobial efficacy compared to uncapped AgNPs due to the bioactive compounds in almond gum, which work in tandem with AgNPs to inhibit microbial growth (Singh *et al*., 2020). Studies have shown that the polysaccharides present in almond gum can further disrupt bacterial biofilm formation, which is often a barrier to effective wound healing (Rai *et al*., 2019). This combination of AgNPs and almond gum creates a potent antimicrobial agent that can effectively prevent and control infections in chronic wounds (Mohanta *et al*., 2020).

Additionally, almond gum-capped AgNPs exhibit improved wound healing properties by reducing oxidative stress at the wound site. The antioxidant activity of almond gum helps neutralize free radicals, thereby protecting cells from oxidative damage and promoting cellular repair mechanisms (Pandey *et al*., 2018). This antioxidant effect complements the action of AgNPs, leading to faster wound closure and reduced risk of infection (Ali *et al*., 2022). Furthermore, almond gum-capped AgNPs enhance fibroblast proliferation and collagen synthesis, key components of tissue regeneration (Balashanmugam *et al*., 2020). In vivo studies have supported the wound-healing efficacy of almond gum-capped AgNPs, showing accelerated healing rates and reduced inflammation in animal models (Raman *et al*., 2021). These results indicate that the green synthesis of AgNPs using Prunus dulcis not only provides a sustainable approach to nanoparticle production but also enhances the biological activity of AgNPs, making them more effective in promoting wound healing.

In Vivo Applications and Efficacy

The in vivo application of Prunus dulcis (almond gum)-capped silver nanoparticles (AgNPs) has shown promising results in promoting wound healing while minimizing adverse effects often associated with conventional wound treatments. The use of almond gum as a natural stabilizing agent not only enhances nanoparticle stability but also contributes to reduced cytotoxicity and improved biocompatibility, making almond gum-capped AgNPs an attractive option for wound care (Gopalakrishnan *et al*., 2021). In animal studies, almond gum-capped AgNPs have demonstrated accelerated wound closure rates, with improved re-epithelialization and tissue regeneration, indicating their potential as a wound healing agent in clinical settings (Kumar *et al*., 2022).

Almond gum-capped AgNPs are particularly effective in reducing inflammation at the wound site. Studies report that these nanoparticles decrease inflammatory cytokine levels while enhancing fibroblast activity, which is crucial for collagen synthesis and tissue repair (Ahmad *et al*., 2020). Additionally, almond gum-capped AgNPs promote angiogenesis, an essential step in tissue repair that enhances blood flow and nutrient delivery to the wound site (Raman *et al*., 2021). Research indicates that animal models treated with almond gum-capped AgNPs show significant reductions in wound size and inflammation within a shorter timeframe compared to untreated or conventionally treated wounds (Ali *et al*., 2022).

Beyond enhanced wound healing, almond gum-capped AgNPs have been found to exhibit potent antimicrobial activity in vivo, reducing bacterial load at the wound site, which is critical for preventing infection in open wounds (González *et al*., 2016). These nanoparticles also have been shown to prevent biofilm formation, a common issue in chronic wounds, thereby supporting faster and more effective healing (Rai *et al*., 2019). Overall, the in vivo efficacy of almond gum-capped AgNPs highlights their potential as a multifaceted treatment option for wound healing applications.

Advantages and Challenges of Almond Gum-Capped AgNPs

Almond gum-capped AgNPs offer numerous advantages, particularly for biomedical applications. One of the primary benefits is the environmentally friendly synthesis process. Unlike traditional AgNP synthesis methods that rely on chemical-reducing agents, green synthesis using almond gum minimizes environmental pollution and reduces toxicity, aligning with current trends in sustainable nanotechnology (Siddiqi *et al*., 2018). Additionally, almond gum, a natural biopolymer, imparts biocompatibility to AgNPs, reducing cytotoxic effects and making them safer for in vivo applications (Rajeshkumar *et al*., 2018). Another significant advantage is the enhanced stability and antimicrobial efficacy of almond gum-capped AgNPs. The natural compounds in almond gum contribute to the long-term stability of the nanoparticles, preventing aggregation and maintaining their bioactivity over extended periods (Bajpai *et al*., 2019). The combined antimicrobial properties of silver ions and almond gum help prevent infection, a primary concern in wound healing, while the gum's antioxidant properties protect the wound site from oxidative stress (Ali *et al*., 2022). Furthermore, almond gum-capped AgNPs promote angiogenesis, collagen deposition, and fibroblast proliferation, providing a multi-faceted approach to wound healing (Balashanmugam & Balakumar, 2020).

Despite these advantages, there are challenges associated with the use of almond gum-capped AgNPs. One of the primary issues is scalability. While green synthesis methods are effective on a small scale, scaling up the production of almond gum-capped AgNPs for commercial applications remains a challenge due to variability in natural gum sources and potential inconsistencies in nanoparticle size and composition (Khan *et al*., 2021). Furthermore, while almond gum generally enhances the biocompatibility of AgNPs, potential toxicity in high doses or long-term exposure still requires thorough investigation in clinical studies (Rahman *et al*., 2021).

In addition, almond gum-capped AgNPs require further optimization to ensure consistent efficacy across different wound types and conditions. The interaction of nanoparticles with the complex wound microenvironment can vary, potentially affecting their performance. To address these issues, additional research is needed to refine synthesis methods, optimize dosages, and conduct comprehensive toxicity assessments to ensure that almond gum-capped AgNPs are safe and effective for widespread clinical use (Mohanta *et al*., 2020).

Conclusion and Future Prospects

In conclusion, *Prunus dulcis* (almond gum)-capped silver nanoparticles (AgNPs) present a compelling approach to enhancing wound healing through green synthesis. By leveraging the natural biocompatibility and stabilizing properties of almond gum, AgNPs exhibit improved stability, reduced toxicity, and potent antimicrobial, anti-inflammatory, and antioxidant properties. These nanoparticles effectively accelerate wound healing by promoting re-epithelialization, collagen synthesis, and angiogenesis, while also minimizing infection risks at the wound site. This eco-friendly synthesis method aligns with the growing focus on sustainable materials in biomedical applications, reducing environmental impact and offering a safer alternative to chemically synthesized nanoparticles. While the potential of AgNPs for wound healing is promising, several challenges and opportunities for future research remain. Large-scale production is a key hurdle, as variability in almond gum sources and the complexity of nanoparticle synthesis can affect batch consistency and efficacy. Future work should focus on optimizing synthesis parameters and developing standardized protocols to ensure reproducibility and scalability for clinical applications. Additionally, while initial studies have demonstrated the safety and efficacy of AgNPs in vivo, more comprehensive investigations are needed to assess potential long-term toxicity, particularly in chronic wound care. Advanced in vivo models and clinical trials will be essential to fully understand the pharmacokinetics, biodistribution, and immune responses associated with AgNPs use in human subjects.

Moreover, there is potential to enhance the functionality of AgNPs by exploring synergistic effects with other biocompatible materials or drug delivery systems to target various wound types and healing stages. Combining almond gum-capped AgNPs with bioactive molecules or growth factors could further enhance wound healing outcomes. Overall, AgNPs@AG offers a promising, sustainable solution for wound care with the potential to contribute significantly to regenerative medicine. Future research should aim to bridge the gap between laboratory efficacy and clinical applicability, paving the way for innovative, environmentally friendly therapies in wound management and beyond.

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