

Review

Green Synthesis of Silver Nanoparticles from *Cannabis sativa*: Properties, Synthesis, Mechanistic Aspects, and Applications

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Abstract: The increasing global focus on green nanotechnology research has spurred the development of environmentally and biologically safe applications for various nanomaterials. Nanotechnology involves crafting diverse nanoparticles in terms of shapes and sizes, with a particular emphasis on environmentally friendly synthesis routes. Among these, biogenic approaches, including plant-based synthesis, are favored for their safety, simplicity, and sustainability. Silver nanoparticles, in particular, have garnered significant attention due to their exceptional effectiveness, biocompatibility, and eco-friendliness. Cannabis (*Cannabis sativa* L.) has emerged as a promising candidate for aiding in the green synthesis of silver nanoparticles. Leveraging the phytochemical constituents of Cannabis, researchers have successfully tailored silver nanoparticles for a wide array of applications, spanning from biomedicine to environmental remediation. This review explores the properties, synthesis mechanisms, and applications of silver nanoparticles obtained from Cannabis. Additionally, it delves into the recent advancements in green synthesis techniques and elucidates the optical properties of these nanoparticles. By shedding light on plant-based fabrication methods for silver nanoparticles and their diverse bionanotechnology applications, this review aims to contribute to the growing body of knowledge in the field of green nanotechnology. Through a comprehensive examination of the synthesis processes, mechanistic aspects, and potential applications, this review underscores the importance of sustainable approaches in nanoparticle synthesis and highlights the potential of Cannabis-derived silver nanoparticles in addressing various societal and environmental challenges.

Keywords: hemolytic activity; green chemistry; phytochemicals; plant-based nanoparticles



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1. Introduction

Green chemistry employs techniques and principles to minimize the use of hazardous substances in chemical production, prioritizing environmental friendliness [1]. There is a growing global recognition of greener production methods for starting materials, especially in organic synthesis, due to their minimal environmental impact [2]. Recent research in green nanotechnology reveals promising environmentally safe applications of various nanoparticles [3]. The primary aim of nanotechnology is to produce nanoparticles with diverse shapes, sizes, and properties to enhance human life [4]. Although chemical and physical methods provide precise control over nanoparticle properties, they often pose environmental and cost challenges [5]. To tackle this, biological organisms are now utilized to synthesize nanoparticles, thus making nanotechnology safer [6]. Over the past decade, nanobiology has made significant progress, with researchers concentrating on developing nanoparticles from living systems, particularly plants [7]. Metals, foremost silver, have been extensively researched for their ability to produce environmentally friendly nanoparticles [8]. Despite substantial research, there is still a need for comprehensive reviews to summarize findings [9]. It is reported that various metals and their oxides, such as

copper (Cu), zinc oxide (ZnO), iron (Fe), and silver (Ag), can be synthesized through the biological reduction of plant extracts. Specifically, in the synthesis of AgNPs, methods such as the co-precipitation technique, green synthesis using leaf extracts, and the use of microorganism-mediated processes are commonly employed to facilitate the reduction and stabilization of silver ions to metallic silver [10]. Silver nanoparticles, alongside other metal nanoparticles, have various applications, including diagnostics, drug delivery, and catalysis, owing to their unique properties [11]. Silver nanoparticles can be synthesized through chemical, physical, and biological methods. Adjusting synthesis conditions can achieve control over properties, as detailed in the references [12]. Investigations into nanoparticle green synthesis have shown the useful effect of plant extract and tissue in making nanoparticles [13]. Hemp, an ancient crop utilized for oil extraction and textiles, possesses various medicinal properties, with its seeds serving as invigorating, purgative, laxative, and pain-relieving agents [14]. Afghanistan is the leading producer, with a cultivation area ranging from 10,000 to 24,000 hectares, as reported by the Afghanistan Ministry of Counter Narcotics and the UNODC [10]. Other significant cannabis-producing nations are reviewed in [15]. Hemp exhibits low tolerance to soil salinity, with sensitivity starting at 42–46 mg/kg of soluble salt. Its agronomic tolerance coefficient to salinity ranges between 62 and 95 mg/kg of soluble salt, placing it among semi-sensitive plants regarding salinity [16].

An ancient crop, hemp, is extensively used in oil extraction and textile industries [17]. Its seeds are valued for their nutritional benefits and hemp seed oil is a prominent product in over 30 countries, including Canada, Japan, and the European Union, widely used in various food products for its nutritional richness [18]. Hemp oil, rich in vitamin E, is contained in approximately 9.10 to 13.9 g per 100 g of seeds, akin to peanut and soybean oils [19]. With a balanced ratio of essential fatty acids, hemp oil provides optimal nutrition for body health [20]. Moreover, hemp offers superior natural fibers, with the separation of long and subcutaneous fibers being preferred over short and fine fibers for industrial applications [21]. Beyond its industrial uses, hemp possesses medicinal properties, often incorporated into painkillers and antiparasitic drugs [22]. Tetrahydrocannabinol (THC, CAS no. 1972-08-3) derived from hemp is renowned for its medicinal effects while the plant's volatile compounds, primarily monoterpenes, find applications in cosmetics and perfumes [23]. Cannabis is classified into three main types, namely, *C. sativa*, *C. indica*, and *C. ruderalis* [24]. Cannabis, tall in stature, is utilized for fiber and seed production and in mental illness treatments. *C. indica*, with its wide leaves, is prevalent in Afghanistan, where its resin is harvested. *C. ruderalis*, a short, unbranched plant, yields minimal medicinal compounds [25]. Previous research [26] classified Cannabis based on phytochemical compounds as follows:

Drug type: THC levels ranging from 1 to 20% and lacking CBD (cannabidiol, CAS no. 13956-29-1), primarily found in hot regions and used for marijuana and hashish production;

Hemp type: Containing less than 0.3% THC and a high CBD concentration, prevalent in northern regions and used for fiber and edible oil production;

Intermediate type: THC levels between 0.3 and 1% and a high CBD concentration, typically found in Mediterranean regions [27].

An alternate classification divides cannabis into two groups: the northern group, known as *C. sativa*, cultivated for fiber and seed oil production around latitudes 30 degrees north, and the southern group, termed *C. indica*, possessing medicinal and intoxicating properties [28].

Hemp, an annual herbaceous plant, typically displays dioecious traits, with separate male and female plants. However, hemp fiber cultivars are mostly monocotyledonous [29]. Cannabis leaves usually have seven lobes, although their number and shape can vary. During the seedling stage, leaves transition from symmetrical to alternate arrangement, with the first pair being single-lobed, the second pair three-lobed, and subsequent leaves five-lobed. While most cannabis plants, especially those native to Central Asia, have no more than five leaves, some can have over thirteen leaves [30]. The leaves are serrated

and claw-shaped, with five to seven leaflets covered in soft, curved unicellular hairs. They spiral upwards along the stem, initially positioned oppositely and gradually becoming singular towards the apex. Leaf arrangement shifts from alternate to reciprocal during growth, a phenomenon termed twisting [31]. Before flowering, leaflets decrease until a small one appears under each pair of sepals. Cannabis leaves typically have dark to light green petioles and usually exhibit nine to fifteen leaflets [32].

Cannabis contains a complex mixture of over 480 compounds, comprising primary building blocks, like amino acids and fatty acids, and secondary components, such as cannabinoids and terpenoids [33]. The bulk of monoterpenes and sesquiterpenes, which are considered essential oils, are synthesized within the plants' glandular structures [34]. Notably, among the cannabinoids, THC (Δ^9 -tetrahydrocannabinol) and cannabidiol (CBD) are the most prominent [35]. Tetrahydrocannabinol is found in minute concentrations (0.3% or less) in the root of seeds and dried stalks of hemp, less than 1% in lower cannabis leaves, and can reach levels of 2–3% in foliage, including the upper leaves of female plants [36]. Bioactive compounds represent secondary metabolites produced by plants as a defense mechanism against various stressors, whether biotic or abiotic. These compounds, spanning several classes, such as phenolic compounds, alkaloids, and terpenes, are gaining increasing recognition across diverse fields. Phenolic compounds found in hemp seeds are predominantly categorized as phenylpropionamides, including phenylamides and lignanamides [37]. The plant seeds have caffeoyltyramine, cannabisin A, and cannabisin B. Several phenylpropionamides found in hemp seeds display important benefits, which are discussed in the next sections. Female inflorescences of cannabis reportedly contain the highest THC content. Cannabis is categorized into drug type (chemotype I) with a high THC/CBD ratio, medium type (chemotype II) with a moderate ratio, and fiber type (chemotype III) with low THC content, primarily used for non-psychoactive purposes like fiber and oil production [38].

This review uniquely integrates diverse research strands on the synthesis of silver nanoparticles from Cannabis, presenting a consolidated view that spans from mechanistic insights to a wide array of applications. While numerous publications have individually explored aspects such as synthesis conditions or specific applications, this article synthesizes these findings to reveal overarching trends, novel synthesis routes facilitated by cannabis bioactive compounds, and unexplored applications in nano biosensing and agricultural engineering. It not only aggregates existing knowledge but critically analyzes gaps and inconsistencies in the current literature, offering a coherent framework that enhances the understanding of silver nanoparticle synthesis using Cannabis. This holistic approach provides significant additional contributions by linking isolated studies into a comprehensive narrative that guides future research directions. In this review, the silver nanoparticle (AgNP) synthesis, important chemical, and environmental factors, AgNP importance, and diverse applications were discussed. It also delves into the mechanisms through which green AgNPs exhibit effectiveness across various applications. Furthermore, the manuscript explores the potential of plant-based AgNPs and their significant implications in different domains.

2. Mechanism of *C. sativa* Bioactive Compounds

A comprehensive exploration into THC's effects led to the revelation of a central nervous system receptor for THC in 1990, subsequently identified as the CB1 receptor [39]. This discovery was followed by the recognition of anandamide in 1992, serving as a significant natural ligand for CB1 [40]. The cloning of the peripheral CB2 receptor in 1993 expanded understanding, followed by discoveries of additional components in the endocannabinoid signaling system. This system regulates various physiological processes, such as memory, inflammation, pain perception, emotions, appetite, metabolism, sleep, stress response, and addiction [41].

CB1 and CB2 receptors, belonging to the G-protein-coupled receptor family, regulate intracellular signaling that influences neurotransmitter release and neuronal excitability [42].

CB1 receptors, primarily situated in nerve terminals, modulate nociception and various physiological functions within the central nervous system [43]. CB2 receptors, located in immune tissues and cells, trigger anti-inflammatory and immunomodulatory effects, assisting in pain alleviation and other bodily processes [44]. THC, which interacts with both CB1 and CB2 receptors, predominantly activates CB1 for its psychoactive and analgesic effects while CB2 mediates its immunomodulatory actions [45]. The activity of THC as an agonist for various receptors and channels, including the elevation of endogenous cannabinoids like anandamide and adenosine, is well-documented [46].

Numerous investigations have highlighted the wide-ranging therapeutic possibilities of cannabidiol (CBD), a non-psychoactive compound, showcasing its effectiveness in alleviating pain, safeguarding neurons, controlling seizures, combating nausea, relaxing muscles, and diminishing inflammation [47]. Unlike THC, CBD demonstrates limited attraction to CB1 and CB2 receptors, instead serving as a potent inhibitor of molecules that activate these receptors [43]. Its ability to reduce inflammation may arise from its function as an antagonist to CB2 receptors [44]. Additionally, CBD interacts with various receptors and channels, such as transient receptor potential channels and serotonin receptors, while also boosting levels of the body's natural cannabinoid, anandamide [40].

3. Plant-Based AgNPs; What Do They Hold?

Silver nanoparticles (AgNPs) have become highly significant in various research fields due to their catalytic properties and antimicrobial potential, including antibacterial and antifungal effects. They are also explored as precursor reagents for biomaterials due to their unique characteristics influenced by factors such as morphology, distribution, and size [48]. In natural environments, plants offer a convenient and abundant source for AgNP synthesis. They are readily available, safe to handle, and contain metabolites with pharmacological components that act as effective reducing agents for AgNP production [49]. This makes medicinal plants particularly promising for generating stable nanoparticles quickly, without the presence of toxic chemicals, using natural capping agents [50].

Traditional techniques for manufacturing AgNPs involve the reduction of silver using metallic salts in water-based solutions [51]. Selecting the reducing agent is critical as it substantially impacts the size of the resulting AgNPs. However, this chemical method often leads to decreased stability and notable agglomeration of the nanoparticles [52]. These challenges can be addressed by employing two-phase liquid-liquid systems utilizing appropriate reducing agents. However, there remains a concern about the potential leakage of chemical agents into the environment with this approach [53]. To overcome these environmental risks, researchers are actively exploring natural compounds derived from plants as efficient alternatives for both reducing and stabilizing AgNPs. By doing so, they aim to achieve consistent nanoparticle size and minimize agglomeration [54]. Embracing the principles of green chemistry, which advocates for environmentally friendly techniques and methodologies, is key to promoting the sustainable synthesis of AgNPs. This eco-conscious approach is widely recognized for its positive impact on both the environment and human health [55]. Investigation into the synthesis of AgNPs utilizing plant-based approaches has yielded nanoparticles with varying sizes, shapes, and morphologies. By utilizing extracts from various plant species, researchers have achieved remarkable versatility in AgNP production. Direct utilization of plants for AgNP synthesis offers advantages in terms of environmental safety and phytomining potential, where plants uptake silver salts and convert them into recoverable AgNPs without affecting plant growth [56]. Plant-based AgNPs also exhibit reduced particle aggregation compared to their chemically synthesized counterparts, making them promising candidates for various applications [50]. Typically ranging from 5 to 100 nm in size, plant-based AgNPs hold significant potential for further exploration and utilization [57].

4. Mechanism of Cannabis-Based AgNP Synthesis: The Pursued Routes

This review presents a detailed procedure for synthesizing silver nanoparticles (Ag-NPs) from Cannabis. The process begins by boiling 2 grams of hemp hurd (HH) in 100 mL of deionized water at 60 °C for one hour. After filtration, the resulting solution, named hemp-hurd-based carbon extract (HHC), is stored at 4 °C [1]. To produce AgNPs, 5 mL of HHC is added to 20 mL solutions containing 1 mM and 5 mM silver nitrate, respectively, and stirred at 70 °C for 30 min. The impact of AgNO₃ concentration and stirring duration on AgNP formation is analyzed. The formation of silver nanoparticles in the HHC medium is confirmed by the distinct brown color observed in the previously clear HHC solution [8]. The eco-friendly synthesis of silver nanoparticles (AgNPs) involved mixing the aqueous leaf extract of *C. sativa* (CSE) with silver nitrate solution (0.25–3 mM) in varying proportions (0.005:1–0.1:1 *v/v*) in Erlenmeyer flasks with continuous stirring. Additionally, pH adjustments were made by changing the pH of the silver nitrate solution from 4 to 11 using 0.1 N solutions of hydrochloric acid (HCl) and potassium hydroxide (KOH) [9]. The impact of incubation time on nanoparticle synthesis was studied over different periods (2–48 h) [11]. To prepare the plant extracts, 25 g of each plant material was mixed with 150 mL of deionized water, heated at 90 °C for 45 min, filtered to remove larger particles, and then cooled to room temperature. Synthesis parameters reported in the literature for nanosilver synthesis were considered during the process [12].

Making silver nanoparticles included mixing plant extracts with silver nitrate (AgNO₃). To get a 0.1 mM AgNO₃ concentration, we dissolved 0.6 g of AgNO₃ salt in 36 milliliters of deionized water and stirred until it was all mixed evenly. Then, 4 mL (10%) of plant extract was added, causing a color change from clear to nearly black within 7 min, indicating AgNP formation. After filtration, the nanosilver particles were purified through ultrasonic washing and dried at 30 °C for 3 h. The resulting solutions contained the nano-silver particles [5]. Figure 1 illustrates the process of creating black-silver nanoparticles from plant extracts by synthesizing from silver ions.

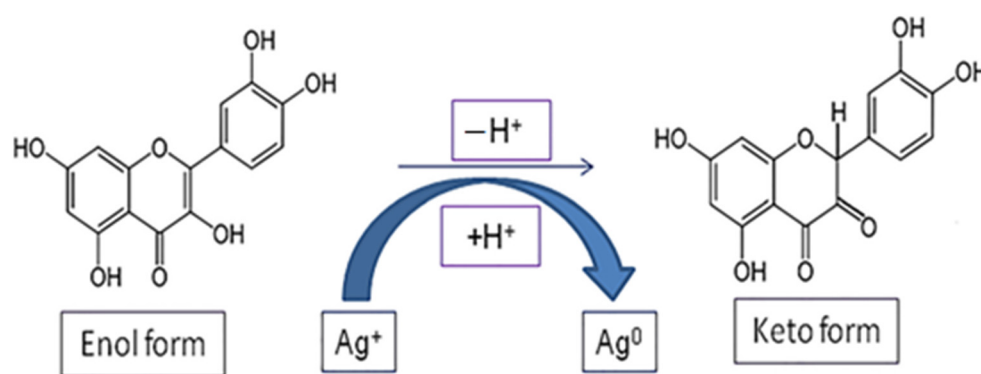


Figure 1. The plant-based synthesis of silver nanoparticles with plant extracts (flavonoids) from silver ions [58].

The potential for environmentally sustainable production of silver nanoparticles from cannabis holds great promise as it taps into the intrinsic properties of cannabinoids and other phytochemicals present in cannabis plants to act as both reducing and stabilizing agents [8]. However, it is imperative to recognize the intricate interplay between the specific cannabis species and the environmental variables during cultivation, which wields significant influence over the synthesis process and the resultant characteristics of the silver nanoparticles [14]. Fluctuations in cannabinoid levels and other bioactive compounds across distinct cannabis varieties can impact their efficacy in reducing silver ions and shaping the morphology of the resulting nanoparticles [9]. Furthermore, environmental factors, such as climate conditions, soil composition, and altitude, play pivotal roles in shaping the chemical composition of cannabis plants, leading to variations in the types and concentrations of compounds available for nanoparticle synthesis [2]. These environmental

nuances can also exert profound effects on the size, shape, and surface properties of the synthesized silver nanoparticles [11]. For instance, variations in temperature, humidity levels, and exposure to sunlight can all influence the growth patterns of cannabis plants, thereby imparting distinct characteristics to the synthesized nanoparticles [5].

The potential of eco-friendly silver nanoparticle synthesis from cannabis is promising, yet the attributes of the nanoparticles may vary based on the cannabis species and environmental conditions during cultivation [3]. The synthesis of silver nanoparticles (AgNPs) relies on a variety of organic compounds present in biological systems, aiding in the reduction of silver ions [6]. These compounds include carbohydrates, lipids, proteins, enzymes, phenolic compounds, flavonoids, terpenoids, and alkaloids. The specific components responsible for silver ion reduction vary depending on the plant extract used. For example, hydrophytic plants utilize ascorbic acid and catechol while exophytic plants rely on cyperquinone, diethequinone, and keto-to-enol conversions. Additionally, factors such as the type and concentration of plant material, as well as various physical parameters, significantly influence the stability and versatility of synthesized nanoparticles [59].

Studies highlight how reaction time, plant extract concentration, and temperature influence the creation of silver nanoparticles, each resulting in unique surface plasmon resonance (SPR) bands [13]. Additionally, terpenoids found in geranium leaves play a significant role in silver nanoparticle synthesis, assisting in the biological reduction of metal nanoparticles within plant extracts [60]. Despite extensive research on silver nanoparticle synthesis from various plant extracts, further exploration is needed to fully understand the implications of these factors on the diverse applications of silver nanoparticles synthesized from cannabis [61].

5. Challenges in Plant-Based AgNP Synthesis

5.1. Incubation Time

Incubation duration significantly impacts the synthesis of silver nanoparticles (AgNPs), influencing yield, stability, and particle size. During experiments using cannabis extract for AgNP synthesis, a swift color change within 2 min indicates the rapid reduction of aqueous AgNO_3 , signaling the initiation of nanoparticle formation [62]. The reaction typically continues for approximately 5 min, marked by further subtle color transitions, resulting in nanoparticles with an average diameter of 12 nm. This quick initial reaction suggests that the bioactive compounds in cannabis extract are highly efficient at reducing silver ions [63]. In contrast, when using *Ocimum sanctum* (Tulsi) leaf extract, stable AgNPs of approximately 17 nm are produced after more prolonged exposure [64]. The yield of biosynthesized AgNPs increases significantly after 15 min of incubation, continuing to rise over subsequent hours [65]. This extended incubation period allows for more complete interactions between silver ions and the reducing agents present in the extract, leading to a higher production of nanoparticles [66]. Similarly, AgNPs synthesized with *Origanum vulgare* L. extract show a higher yield with longer reaction times, up to 3 h. These observations underscore that prolonged incubation times enhance the reduction process of silver ions, facilitated by the sustained availability and activity of reducing agents in the plant extracts [67]. The increased contact time between the silver ions and bioactive molecules results in more efficient reduction and stabilization, culminating in greater nanoparticle production [68].

5.2. pH

The pH of the reaction medium plays a crucial role in the synthesis of silver nanoparticles (AgNPs) from cannabis extracts. Previous research [69] reported that a neutral pH of 7 was optimal for the reduction of silver ions to AgNPs, with efficient nanoparticle production observed between pH 7 and 9 [70]. At these pH levels, the plant extract's hydroxyl (OH) groups are more active in reducing silver ions, thus facilitating the formation of stable and abundant nanoparticles. This was evidenced by the rapid formation of nanoparticles and their spherical shape, particularly noted at pH 8 where the synthesis was most favorable [71].

Further studies [72] have shown that pH adjustments can significantly influence AgNP characteristics. Solutions prepared at a slightly basic pH of 8.9 ± 0.15 exhibited a characteristic yellow color, indicative of AgNP formation. In contrast, those at acidic conditions ($\text{pH } 4.2 \pm 0.10$ and 2.3 ± 0.32) displayed a gray color, suggesting nanoparticle aggregation [73]. Spectral analysis revealed a distinct surface plasmon resonance band around 390 nm, confirming the spherical nature of AgNPs at this optimal pH. The narrower full width at half maximum (FWHM) at extreme pH values indicated smaller nanoparticles while a broader band within the pH range of 3–7 suggested aggregation due to less favorable conditions [74]. Regarding the effects at a higher pH (greater than 9), the environment can become too basic, potentially leading to the oversaturation of hydroxyl ions, which might cause excessive aggregation or instability of the nanoparticles [75]. Although higher pH values can initially promote rapid nanoparticle formation, they may eventually lead to suboptimal conditions for controlling nanoparticle size and dispersion due to the altered behavior of stabilizing agents in the plant extracts. Therefore, maintaining a pH close to 7 provides a balanced environment that maximizes the efficiency and stability of AgNP synthesis, leveraging the optimal activity of hydroxyl groups without inducing the negative effects seen at more extreme pH levels [76].

5.3. Light Intensity

Light intensity is a crucial factor that significantly impacts the synthesis of silver nanoparticles (AgNPs), particularly in green synthesis methods. Utilizing sunlight, which includes a spectrum of wavelengths, has proven beneficial for green synthesis processes involving medicinal plant extracts, such as the *Sida retusa* leaf, *Piper longum* catkin extract, and *Carica papaya* fruit [77]. Studies have shown that higher light intensities correlate with increased absorbance, suggesting a faster reduction of Ag^+ ions under conditions of intense sunlight compared to darker environments [78]. This acceleration is largely attributed to the specific wavelengths within the sunlight, particularly ultraviolet (UV) light, which catalyzes the green synthesis process, facilitating rapid AgNP formation [79].

The role of UV light is particularly notable as it provides energy that enhances the reduction of silver ions. Sunlight-based synthesis not only accelerates the process but also enhances the yield and stability of the produced AgNPs [80]. Furthermore, experimental explorations of different light colors revealed that violet light filters significantly improve the synthesis of AgNPs by enhancing specific light wavelengths conducive to the reaction [81]. The wavelength of light, particularly UV, plays a significant role in defining the electronic properties and optical band gap of the AgNPs [80]. The energy provided by UV light can alter the electronic structure of the nanoparticles, potentially modifying their optical band gap. This relationship between the light wavelength and the nanoparticles' properties is crucial for optimizing the synthesis process and tailoring the nanoparticles' characteristics for specific applications [82].

5.4. Temperature

Temperature plays a pivotal role in synthesizing silver nanoparticles (AgNPs), influencing their size, shape, and overall morphology. It is well-documented that higher reaction temperatures generally lead to the formation of smaller, more uniformly spherical AgNPs [83]. This phenomenon is attributed to enhanced kinetic energy at elevated temperatures, which promotes rapid nucleation rates. As reported previously [84], the increase in temperature from 25°C to 75°C resulted in a decrease in nanoparticle size from 20 nm to 5 nm due to increased nucleation [85]. Conversely, lower temperatures slow the nucleation process, leading to longer growth phases, which typically result in larger nanoparticles. This is supported by previous research [86], which reported that reducing the synthesis temperature from 80°C to 30°C increased the average particle size from 10 nm to 25 nm [87].

Various plant extracts demonstrate different efficiencies at various temperatures. For instance, previous research [88] showed that the extract of *Moringa oleifera* was able to

effectively reduce Ag^+ ions and stabilize AgNPs, even at a lower temperature of 40 °C, highlighting the plant's robust catalytic properties under milder conditions [89]. In contrast, extracts from *Eucalyptus globulus* demonstrated optimal synthesis and stability of AgNPs within a temperature range of 60 °C to 80 °C, as optimal phytochemical activity was observed within this range [90].

Despite these observations, the detailed impact of specific temperature settings on nanoparticle characteristics, such as size distribution and shape consistency, is not always thoroughly documented in existing studies [91]. For example, while reference [84] discusses the general trend of temperature effects on nanoparticle size, it lacks detailed experimental data on specific temperatures used during synthesis. This gap underscores the need for further controlled experiments to elucidate the temperature dependency of AgNP size and morphology more comprehensively [92]. Additionally, understanding the interaction between plant extract components and temperature could further refine the synthesis process, tailoring nanoparticle characteristics for specific applications. It is noticeable that in the green synthesis of silver nanoparticles (AgNPs) using cannabis extract, as presented in Table 1, the predominant morphology observed is spherical. This shape is commonly reported in green synthesis methodologies due to the isotropic growth conditions typically favored by the natural reducing agents found in plant extracts, including cannabis. The inherent properties of cannabis, particularly the presence of various cannabinoids and terpenes, facilitate the reduction of AgNO_3 to AgNPs in a manner that tends to promote spherical structures.

While spherical nanoparticles are prevalent due to their straightforward synthesis under standard reaction conditions, it is important to note that the shape of nanoparticles can significantly influence their physical and chemical properties and, subsequently, their application potential in areas such as medicine, catalysis, and electronics [93]. The ability to control the morphology of nanoparticles is thus of considerable interest for enhancing their functionalization [94]. Different shapes of nanoparticles, such as rods, triangles, or cubes, can be synthesized by modifying certain parameters in the green synthesis process. These modifications might include altering the concentration of Cannabis extract, adjusting the pH of the reaction mixture, varying the reaction temperature and time, or introducing additional shape-directing agents [95]. For instance, the presence of certain cannabinoids or specific terpenes might inhibit or promote the growth of AgNPs in particular directions, leading to non-spherical shapes.

Although our current study focuses on spherical nanoparticles, the potential for synthesizing AgNPs of various morphologies using cannabis extract remains an intriguing area for future research. Adjustments in the synthesis conditions could allow for the tailored fabrication of nanoparticles with specific shapes, catering to the needs of diverse applications and thus expanding the utility of cannabis-derived AgNPs [96].

This area of study not only broadens the scope of nanoparticle synthesis using green chemistry principles but also enhances our understanding of the interaction between biological molecules and inorganic ions at the nano–bio interface [97]. Continued research into the morphology control of nanoparticles using cannabis and other plant extracts will contribute significantly to the field of nanotechnology, particularly in the development of environmentally friendly synthesis methods [98]. The effect of different factors on silver nanoparticle synthesis is shown in Table 1.

Table 1. Influence of different factors on silver nanoparticle synthesis.

Preparation Method	Reducing Agent	Conc. of AgNO ₃	Crystallite Size (nm) ^c	pH	Temp. °C	Particle Size (nm) ^d	Amax, (nm)	Reference
Green synthesis ^a	<i>Acacia raddiana</i> leave extract (25 mL)	5 mM	35.5	10	70	8–41 (spherical)	423	[99]
Green synthesis ^a	Leaf extract of <i>Acer pento-pomicum</i> (1 mL)	1 mM	9.5	6–7	35–55	19–25 (spherical)	450	[100]
Green synthesis ^a	<i>Acalypho hispido</i> leaf extract (10.5 mL)	1.75 mM	-	-	50	20–50 (spherical)	-	[101]
Green synthesis ^b	<i>Aloefera</i> (15%)	5 mM	-	-	60	34–102 (spherical)	420	[102]
Green synthesis ^b	<i>Boswellia ovalifolio</i> (5 mL)	0.01 M	15	-	-	-	455	[103]
Green synthesis ^b	<i>Clitoria ternatea</i> (5 mL)	0.1 M	20	9	-	-	420	[104]

^a Aqueous extraction: This involves boiling the desired plant parts in water or simmering them at lower temperatures to obtain water-soluble organic compounds. ^b Alcoholic extraction: Using ethanol or methanol as solvents to extract non-polar to moderately polar compounds, which might have strong reducing capabilities. ^c Crystallite size determination methods vary; typically, X-ray diffraction (XRD) analysis using the Scherrer equation is employed. ^d Particle size was measured using dynamic light scattering (DLS) or transmission electron microscopy (TEM), as specified in individual studies. Amax: the wavelength of maximum absorbance, measured in nanometers (nm).

The stability of silver nanoparticles (AgNPs) synthesized using cannabis extract is a critical factor that determines their suitability for various applications. Stability in the context of nanoparticles refers to the ability of the particles to maintain their size, shape, dispersion, and chemical properties over time [105]. For AgNPs synthesized using green synthesis methods, including those derived from cannabis extracts, several factors contribute to their stability.

The natural phytochemicals in cannabis, such as cannabinoids and terpenes, play a dual role as both reducing and stabilizing agents [106]. These organic compounds coat the surface of the nanoparticles, preventing agglomeration and oxidation, which are common challenges in nanoparticle storage and use. However, depending on the intended application and environmental conditions, the intrinsic stability provided by cannabis extracts might be insufficient [107].

To enhance the stability of AgNPs, additional organic stabilizing agents can be employed. These agents function by forming a protective layer around the nanoparticles, further preventing agglomeration, and enhancing their biocompatibility [108]. Commonly used organic stabilizers include polysaccharides, proteins, and peptides. Polysaccharides, such as alginate, chitosan, and starch, are biocompatible and can enhance the stability of nanoparticles in biological environments [109]. Proteins and peptides, such as albumin, gelatin, and specific peptides, can bind to the surface of AgNPs, providing stability and functional capabilities, particularly for medical applications [110]. Additional plant-derived compounds, apart from the primary cannabis extract used for synthesis, are plant extracts, such as aloe vera gel and tea extracts, containing antioxidants and other phytochemicals that contribute to the stability of nanoparticles [111].

Incorporating these stabilizers during or after the synthesis process can tailor the dispersion stability, shelf-life, and functional attributes of AgNPs. For instance, coating AgNPs with polysaccharides like chitosan not only stabilizes them but also enhances their antimicrobial properties, making them more effective for applications in wound dressings and antibacterial coatings [112].

6. Cannabis-Based AgNO₃ Functional Groups

Comprehending the functional groups present in extracts from *C. sativa* and how they interact with silver ions is vital for understanding the mechanisms involved in generating and stabilizing silver nanoparticles (AgNPs) using these extracts [113]. Techniques like

Fourier-transform infrared spectroscopy (FTIR) are crucial for identifying specific functional groups involved in AgNP synthesis from *C. sativa*. These functional groups likely play crucial roles in stabilizing and facilitating AgNP formation [114]. In *C. sativa* extracts, various potential functional groups interact with silver ions during AgNP synthesis, including phenolic compounds, terpenoids, carboxylic acids, amino acids and amines, and sulfur-containing compounds [115]. Phenolic compounds like flavonoids and phenolic acids found in *C. sativa* may serve as both reducing agents and stabilizers for AgNP formation. Terpenoids, including cannabinoids, such as cannabidiol and tetrahydrocannabinol, may contain hydroxyl groups (OH) that contribute to reducing and stabilizing silver ions during nanoparticle synthesis. Carboxylic acids from cannabinoids like cannabidiolic acid (CBDA) and tetrahydrocannabinolic acid (THCA) can act as reducing agents and stabilizers for AgNPs [116]. Though less common, amino acids and amines present in *C. sativa* extracts may also interact with silver ions during nanoparticle synthesis, potentially aiding in reducing and stabilizing silver nanoparticles [117]. Additionally, sulfur-containing compounds, like thiols and sulfides, may be present in *C. sativa* extracts, possibly interacting with silver ions and assisting in the synthesis and stabilization of silver nanoparticles.

7. Application of Cannabis-Based AgNPs

Antibacterial Properties of AgNPs

Silver nanoparticles (AgNPs) are renowned for their inherent antibacterial properties, which are primarily due to their substantial surface-area-to-volume ratio. This physical characteristic enhances their interaction with bacterial cell membranes, leading to membrane disruption and subsequent cell lysis [118]. Additionally, AgNPs can penetrate bacterial cells, disrupting vital cellular processes, such as DNA replication and protein synthesis, thereby contributing significantly to their bactericidal effects [119].

The antibacterial mechanism of silver nanoparticles is multifaceted. Initially, AgNPs interact with bacterial membranes, causing structural disruptions or penetrating the bacterial cytoplasm. Once inside, they induce metabolic disruption, leading ultimately to bacterial death [120]. Additionally, AgNPs are known to generate reactive oxygen species (ROS), which further contribute to bacterial cell damage and death by disrupting cellular integrity and function [121]. Another critical aspect of AgNPs' antibacterial action involves the gradual release of silver ions (Ag^+), which are highly toxic to bacterial cells. These ions bind to and deactivate essential bacterial enzymes and proteins, interrupting critical cellular functions and leading to cell death [122]. This ion-release mechanism is particularly effective and forms the basis for many of the current applications of AgNPs in antibacterial coatings and medical devices.

Moreover, silver nanoparticles demonstrate varying degrees of efficacy against different types of bacteria. Research indicates that AgNPs are more effective against Gram-positive bacteria, such as *Staphylococcus aureus*, due to the structural peculiarities of Gram-positive cell walls, which allow easier penetration of nanoparticles. In contrast, their action against Gram-negative bacteria, like *Escherichia coli*, *Pseudomonas aeruginosa*, and *Klebsiella pneumoniae*, involves complex interactions with outer membrane proteins and the periplasmic space, which may also lead to the disruption of the bacterial membrane integrity [123].

Recent studies have expanded the potential applications of AgNPs, exploring their use in conjunction with other biopolymers, such as chitosan. Chitosan-mediated AgNP synthesis has been shown to enhance antibacterial activity, likely due to the synergistic effects of chitosan's cationic nature and the nanoparticle's ability to disrupt bacterial membranes [124]. This combination has proven particularly effective in creating more stable and biocompatible formulations for medical use. Biosynthesized silver nanoparticles hold significant promise as potent antibacterial agents. Their diverse mechanisms of action, combined with their ability to be engineered for specific applications, make them a valuable tool in the fight against bacterial infections [125]. Ongoing research and development are expected to further define their role in medicine, particularly in developing strategies to

combat antibiotic-resistant bacterial strains and enhancing their effectiveness in clinical settings [126].

8. Mechanisms of Antibacterial Action

Recent studies highlight three primary mechanisms by which silver nanoparticles (AgNPs) combat bacteria: penetration of bacterial membranes causing cell death, disruption of internal cell components including DNA and proteins, and release of silver ions interfering with cellular processes [127]. Researchers tested the antibacterial effectiveness of AgNPs against both Gram-positive (*S. aureus*) and Gram-negative (*E. coli*) bacteria, assessing minimum inhibitory and bactericidal concentrations (MIC and MBC) using a broth dilution method covering a concentration range of 0 to 500 mg L⁻¹ [128].

Factors Affecting the Antibacterial Activity of AgNPs

Researchers have explored how the properties of AgNPs, like size and surface characteristics, influence their effectiveness against bacteria [129]. Previous studies looked at how nanoparticle size affects their ability to combat dental bacteria. They created AgNPs of different sizes (5, 15, and 55 nm) and found that 5 nm nanoparticles were the most effective, with varying minimum inhibitory concentrations (MICs) for different microorganisms [130]. The difference in MIC values was attributed to *Escherichia coli*'s aerobic nature compared to other anaerobic bacteria. The study suggested that the oxidation of AgNPs in water upon exposure to air might reduce their antibacterial potency [131].

In a separate investigation, researchers synthesized AgNPs of different dimensions using similar constituents and procedures, tweaking pH levels and ratios of agents responsible for reduction and stabilization [132]. Subsequently, they assessed the antimicrobial potency of nanoparticles spanning from 5 to 100 nanometers against both Gram-negative and Gram-positive bacteria [133]. The determined minimum inhibitory concentration (MIC) fluctuated between 20 and 110 micrograms per milliliter, 60 and 160 micrograms per milliliter, 30 and 120 micrograms per milliliter, and 70 and 200 micrograms per milliliter for *E. coli*, *Bacillus subtilis*, and *Staphylococcus aureus*, respectively. Interestingly, smaller nanoparticles (5 nm) exhibited reduced minimum inhibitory concentration (MIC) values, whereas larger nanoparticles (100 nm) were associated with elevated MIC values [134]. This phenomenon can be attributed to the increased surface area to volume ratio of smaller nanoparticles, which enhances their interaction with microbial cells. Smaller silver nanoparticles are more efficient at penetrating the bacterial cell wall and membrane due to their size, which allows them to disrupt cellular processes more effectively than their larger counterparts [135]. Once inside the cells, these nanoparticles can interact with vital biomolecules, such as DNA and proteins, inhibiting essential functions like replication and enzyme activity. Additionally, smaller nanoparticles have a higher surface reactivity, which increases the release rate of ionic silver—known for its strong antimicrobial properties—from the nanoparticle surface [136]. This release contributes further to their potent antibacterial activity by generating reactive oxygen species (ROS) and interfering with the bacterial respiratory chain, leading to increased oxidative stress and cellular damage [137]. Therefore, the size of silver nanoparticles plays a crucial role in determining their efficacy as antibacterial agents, with smaller particles generally showing superior performance due to their enhanced ability to interact with and disrupt bacterial cells. Additionally, bactericidal concentrations ranged from 30 to 140 micrograms per milliliter for all strains, except for *Staphylococcus aureus*, wherein the minimal bactericidal concentration (MBC) surpassed 200 micrograms per milliliter [138]. These results underscored a notable correlation between nanoparticle size and antibacterial efficacy, ascribed to the expanded surface area of smaller nanoparticles facilitating improved interaction with bacterial cells [139].

In a recent investigation [140] focusing on potential adverse effects, scientists produced five distinct silver nanoparticles (AgNPs) using chemical reduction methods and explored their inhibitory effects against *Escherichia coli* and *Pseudomonas aeruginosa*. The results indicated that smaller nanoparticles (15 to 50 nm) exhibited notable inhibition, creating

inhibition zones of 8 mm for *P. aeruginosa* and 1.5 mm for *E. coli* [141]. Conversely, larger nanoparticles (30 to 200 nm aggregates) displayed reduced activity, with inhibition zones of only 0.8 mm for *P. aeruginosa* and 0.7 mm for *E. coli*. A recent investigation further emphasized a reverse correlation between antibacterial effectiveness and nanoparticle size against *E. coli*, with nanoparticles averaging 19 nm demonstrating the highest antibacterial potency, potentially due to increased levels of reactive oxygen species generated by smaller AgNPs.

In summary, nanoparticles capped with positively charged groups show enhanced antibacterial activity due to the electrostatic attraction between these AgNPs and the negatively charged bacterial cells, enhancing their interaction and efficacy [142]. Although the synthesis yields Ag⁰ nanoparticles, subsequent interactions with capping agents from the extract can impart a positive charge, influencing both the release rate of silver ions and their antibacterial potency. Smaller nanoparticles dissolve more rapidly, releasing ions that significantly boost their antibacterial action [143].

The coating of nanoparticles serves as the principal connection between nanoparticles and the surrounding environment, influencing their antibacterial effects. This coating can be modified by introducing various agents during synthesis or subsequent stages [144]. Depending on the desired outcome, nanoparticles can be synthesized with chemical agents possessing inherent antibacterial properties to impart similar traits to the final product [145]. Coating nanoparticles with polymers or organic compounds has been shown to yield nanoparticles that are non-toxic or minimally toxic to mammalian cells while retaining effectiveness against bacteria [146]. For instance, utilizing chitosan to coat AgNPs has exhibited robust inhibitory effects against bacteria, such as *S. aureus*, *P. aeruginosa*, and *Salmonella typhimurium*, substantially reducing colony counts after brief exposure [147].

Research has elucidated how the properties of AgNPs influence their antibacterial activity, impacting the mechanisms of interaction with bacteria [148]. Factors facilitating nanoparticle–bacterial cell interactions and entry enhance their antimicrobial efficacy. The variability in antibacterial activity based on nanoparticle properties allows for tailored manipulation and fabrication to achieve specific objectives, leading to the development of antimicrobial agents with optimized characteristics [149]. In this context, several advantages of employing nanoparticles against bacteria are apparent, including their small size facilitating effective penetration through tissue barriers, solubility, and multiple antibacterial mechanisms, reducing the likelihood of bacterial resistance to this nanomaterial [150]. Silver NPs can be combined with antibiotics, see Table 2.

Table 2. A resume of research addressing the use of AgNPs combined with antibiotics.

Antibiotics Used with AgNP	Bacteria Tested	Antibacterial Parameters	Reference
Chloramphenicol, Kanamycin	<i>S. typhimurium</i> , <i>B. subtilis</i>	The cooperative and enhancing impact of combining AgNPs with chloramphenicol and AgNPs with kanamycin, as per the Fractional Inhibitory Concentration Index (FICI) ¹ of 1, was observed.	[151]
Azlocillin	<i>P. aeruginosa</i>	The antibacterial efficacy of azlocillin was boosted when combined with AgNPs, reducing the minimum inhibitory concentration (MIC) from 8 ppm when used alone to 4 ppm when combined with AgNPs.	[152]
Erythromycin	<i>S. oralis</i> , <i>Enterococcus faecalis</i> , <i>E. coli</i> , <i>A. actinomycetemcomitans</i>	When the antibiotic was combined with AgNPs, its antibacterial effectiveness increased synergistically, transitioning from no growth inhibition to falling within the susceptible range.	[153]
Vancomycin	<i>E. coli</i> , <i>S. aureus</i>	The synergistic antibacterial effects were observed with AgNPs functionalized with antibiotics. Notably, <i>E. coli</i> shifted from being resistant to vancomycin to becoming susceptible.	[154]
Ampicillin	Ampicillin resistant <i>S. aureus</i> , <i>K. pneumonia</i> and <i>P. aeruginosa</i>	The minimum inhibitory concentration (MIC) of AgNPs synthesized with ampicillin ranged from 3 to 28 µg/mL against all tested bacteria, compared to 12 to over 720 µg/mL for ampicillin alone.	[155]
Ampicillin	<i>E. coli</i> , <i>E. aerogenes</i> ampicillin resistant, <i>S. aureus</i>	Ampicillin-functionalized AgNPs significantly reduced colony-forming units (CFU) in all tested bacteria, including resistant strains.	[156]

¹ FICI = fractional inhibitory concentration index.

9. Evaluation of the Antioxidant Activity of *Cannabis-sativa*-Derived AgNPs

Antioxidants play a vital role in protecting biological systems against oxidative stress, which is associated with various diseases and the aging process [157]. In this study, the antioxidant potential of silver nanoparticles (AgNPs) synthesized from *C. sativa* extracts was evaluated, utilizing their unique properties derived from both the nanoparticle form and the botanical source. The antioxidant capacity of these AgNPs is crucial for understanding their potential health benefits and therapeutic applications [158].

Among the *in vitro* assays utilized, the DPPH (2,2-diphenyl-1-picrylhydrazyl) assay is a common method for assessing the ability of antioxidants to neutralize the stable DPPH radical [159]. For AgNPs derived from *C. sativa*, this assay is particularly telling as it reflects how the unique phytochemical composition of the cannabis extract enhances the antioxidant properties of the nanoparticles. The assay's color change from purple to yellow, indicating radical reduction, showcases the effective scavenging ability of these nanoparticles [160]. However, it is important to note the limitations of the DPPH assay, such as non-linear response curves and potential interference by other compounds in the extract, which necessitate careful interpretation of the results.

Additionally, the ABTS (2,2'-azinobis-(3-ethylbenzothiazoline-6-sulfonate)) assay was employed to measure the AgNPs' capacity to counteract the ABTS radical cation. This method is preferred for its rapidity and sensitivity, allowing efficient screening of the antioxidant activity of *Cannabis-sativa*-derived AgNPs [161]. The versatility of the ABTS assay to operate in both aqueous and organic solvents makes it particularly suitable for testing the diverse solubility profiles of cannabis-based nanoparticles, providing broader insights into their antioxidant effectiveness across different environments [162].

Furthermore, specific assays targeting reactive oxygen species (ROS), such as hydroxyl radical scavenging, superoxide anion scavenging, and nitric oxide scavenging, were utilized to assess the comprehensive antioxidant profile of these AgNPs [163]. The results from these assays contribute to a detailed understanding of how the phenolic compounds, flavonoids, and carotenoids inherent in *C. sativa* extracts impart antioxidant properties to the synthesized nanoparticles.

In conclusion, the evaluation of antioxidant activities in *Cannabis-sativa*-derived AgNPs using various *in vitro* assays underscores the significance of both the synthesis method and the source material [164]. This approach not only confirms the potent antioxidant capabilities of the AgNPs but also highlights their potential as therapeutic agents, leveraging the unique properties of *C. sativa*. Ongoing research is necessary to further optimize assay conditions and fully characterize the interactions between cannabis phytochemicals and silver nanoparticles to maximize their health-promoting effects [165].

10. Evaluation of Hemolytic Activity

Nanomaterials possess the capability to enter the bloodstream and interact with vital blood cells, necessitating a comprehensive examination of their impact on these cells [166]. A study investigating the effects of both *C. sativa* root extract and artificially produced silver nanoparticles on human red blood cells (RBCs) at varying concentrations revealed that the highest degree of hemolysis occurred at the maximum concentration of plant extract and AgNPs, registering percentages of $1.55 \pm 0.07\%$ and $6.47 \pm 0.04\%$, respectively [167]. Conversely, at the lowest concentration tested ($10 \mu\text{g/mL}$), the level of hemolysis declined to 0% and 0.1% for the plant extract and AgNPs, respectively. Remarkably, at a concentration of $5 \mu\text{g/mL}$, neither the plant extract nor the AgNPs induced hemolysis [168].

In contrast, investigations into the hemolytic effects of polymeric nanoparticles observed hemolysis exceeding 10% at a concentration of $40 \mu\text{g/mL}$. Prior research on the ethanolic extract of *C. sativa* indicated minimal hemolytic activity ranging from 1.97% to 5.88% [169]. Additionally, hemolytic activity was even lower (below 5%) for silver nanoparticles synthesized using fenugreek and papaya leaves. Nevertheless, the mechanisms underlying hemolysis by AgNPs in erythrocytes remain ambiguous. It remains uncertain whether the observed hemolysis results from direct interactions between particles and cells,

the liberation of free silver ions, or a combination of both [167]. Nonetheless, the study's discovery of relatively low hemolytic activity suggests promising biomedical prospects for AgNPs synthesized from *C. sativa*.

11. Nanobiosensors

Nanoparticles offer distinctive features that make them well-suited for biosensors as they can be detected using various techniques, such as optical absorption, fluorescence, and electrical conductivity [170]. Silver nanoparticles (AgNPs) stand out for their remarkable sensitivity in measurements, largely due to surface plasmon resonance (SPR) [171]. The unique physical and chemical characteristics of metals at the nanoscale have paved the way for a diverse range of biosensors, including nanobiosensors utilized in disease diagnosis, monitoring disease progression or treatment, and cell tracking, as well as nanoprobe for in vivo detection and imaging, among other applications driven by nanotechnology [172,173].

12. Agricultural Engineering

The emergence of nanoscale lignocellulosic materials from crops and trees has sparked a rising market for innovative and valuable nanoproducts [174]. These materials are now applied in diverse sectors, such as food packaging, automotive construction, and agricultural practices [175]. Nanofertilizers, nanopesticides, nanoherbicides, nanocoatings, and intelligent delivery systems for plant nutrients are increasingly integrated into farming methods. Typically containing silver nanoparticles (AgNPs) sized between 100 and 250 nm, these nanoproducts boast enhanced water solubility, thus increasing their effectiveness [176]. Nanofertilizers offer a distinct advantage by aligning nutrient release with plant uptake, reducing nutrient losses, and minimizing groundwater pollution risks [177]. Engineered to release nutrients precisely when plants need them, nanofertilizers prevent their conversion into less plant-accessible forms [178]. This precision is achieved by controlling nutrient interactions with microorganisms, water, and soil, ensuring nutrients are only released when plants can directly utilize them.

13. Toxicological Limitations of Silver Nanoparticles

Silver nanoparticles (AgNPs) are increasingly utilized in various commercial products worldwide, particularly in biological applications. However, concerns persist regarding their potential harm to living organisms and the environment, necessitating stringent safety measures [179]. Despite their widespread use, comprehensive data on AgNP exposure and toxicity remain limited, underscoring the need for further research [180].

Some studies suggest that certain organisms may exhibit heightened sensitivity to AgNPs compared to free silver ions (Ag^+), highlighting the complexity of their interactions. Additionally, the release of AgNPs into the environment from various sources, such as medical and household products, is poorly understood, contributing to environmental concerns [181]. Further investigation is needed to understand the fate of AgNPs in the environment and their potential impacts on ecosystems and human health [182]. Recent inquiries have focused on human exposure to AgNPs from commercial products, yet comprehensive studies on their environmental and toxicological effects are lacking. Addressing knowledge gaps in AgNP behavior and toxicity is crucial for informing regulatory policies and developing strategies to mitigate environmental risks [183].

14. Conclusions

The rise of silver nanoparticles (AgNPs) synthesized via environmentally friendly routes heralds a significant breakthrough across multiple domains, particularly due to their safety, compatibility with living organisms, and robust antimicrobial properties. These eco-conscious AgNPs are poised to revolutionize various sectors, mirroring the advancements made by their conventionally synthesized counterparts. Plant-based silver nanoparticles (AgNPs) offer a promising solution to fight against antimicrobial resistance. They are

safe to use and have strong antimicrobial effects, which could help create new medicines to fight a wide range of germs. The market for AgNPs is growing fast and offers great opportunities, especially for things like quick medical tests, diagnostics, vaccines, and household products. But to make the most of them, we need to invest in research to make sure AgNPs made from plants are as effective as those made chemically. Through concerted research endeavors, plant-based AgNPs can be fine-tuned for a diverse array of applications, unlocking their immense potential across a multitude of industries. Green synthesis offers distinctive advantages over conventional chemical methods, including cost-effectiveness, environmental sustainability, and scalability for large-scale production. Thus, prioritizing research and development efforts towards plant-based AgNP synthesis holds great promise for fully realizing their capabilities across various applications. In addition to the synthesis of silver nanoparticles, recent studies have also explored the green synthesis of gold nanoparticles using *C. sativa* extracts. Like their silver counterparts, these gold nanoparticles exhibit unique properties beneficial for applications in catalysis, sensing, and medical imaging. This parallel development underscores the versatility of *C. sativa* as a reducing agent, highlighting its potential in synthesizing various types of metallic nanoparticles that could be pivotal for future technological and medicinal applications.

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