Physics Spectrum Journal
Volume 01 Issue 01, January 2026
P-ISSN: xxxx-xxxx, E-ISSN: xxxx-xxxx

A Review on Limau Kuit (Citrus hystrix DC) Peel Extract as a Sustainable Capping Agent for Silver Nanoparticles (AgNPs)

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Article Info

Article info:
Received: xx-xx-20xx
Revised: xx-xx-20xx
Accepted: xx-xx-20xx

Keywords:
Silver Nanoparticles (AgNPs), Extract of Limau kuit Peel, Capping Agent

How To Cite:
xxxxxx

DOI:
xxxxx

Abstract

This paper examines the efficacy of lime peel extract in the manufacture of silver nanoparticles (AgNPs) as a capping agent and its extensive applications across many sectors. Lime peel extract comprises secondary metabolites, including flavonoids, terpenoids, and phenolic acids, which serve to stabilize AgNPs, inhibit agglomeration, and regulate particle size and dispersion. The synthesis of AgNPs utilizing this extract yields nanoparticles measuring approximately 10-50 nm, exhibiting a uniform and stable shape. Diverse extraction methods, including maceration and ultrasonication, have been employed to efficiently acquire these bioactive chemicals. The resultant AgNPs possess extensive uses, particularly in waste management, biomedicine, and electronics and sensors. In waste processing, AgNPs facilitate pollutant adsorption and redox processes to eliminate pollutants. In the biomedical domain, AgNPs exhibit potential as antibacterial agents and in medication delivery, whereas in the electronics and sensors sector, AgNPs are employed in the creation of biosensors, gas sensors, and energy storage devices. Notwithstanding their significant promise, issues about the long-term stability and toxicity of AgNPs must be resolved by additional research. This research demonstrates that AgNPs manufactured using lime peel extract provide an eco-friendly and efficient alternative for diverse industrial and environmental applications.

1. Introduction

Nanotechnology has emerged as a fundamental element of innovation across multiple areas, including waste management, healthcare, electronics, and sensing. Silver nanoparticles (AgNPs) are garnering interest among produced nanomaterials due to their distinctive features, including

antibacterial efficacy, catalytic capability, and optical stability. The demand for sustainable synthesis methods of AgNPs is becoming increasingly urgent due to their many uses, including wastewater treatment, antibacterial compounds, and sensitive electronic components [1]. Traditional techniques employing chemical reducing agents, like borohydride, encounter difficulties due to the hazardous waste generated, rendering them inconsistent with green chemistry principles [2].
An environmentally sustainable alternative utilizes natural components as reducing agents and stabilizers (capping agents). This biologically oriented method employs beneficial substances derived from plant extracts or agricultural byproducts to substitute detrimental chemicals. Plant extracts contain diverse active compounds, including flavonoids, polyphenols, and tannins, which serve as reducing agents and inhibit the agglomeration of nanoparticles during and post-synthesis [3]. In this context, limau kuit (Citrus hystrix), often located in Southeast Asia, presents significant potential as a natural capping agent in the synthesis of AgNPs.

Citrus hystrix are recognized for their abundance of bioactive chemicals that offer numerous advantages. The skin contains abundant flavonoids, polyphenols, ascorbic acid, and essential oils. These compounds possess robust antioxidant properties, enabling them to function as efficient reducing agents in the nanoparticle manufacturing process [4]. The compound structure stabilizes the nanoparticles by creating a protective coating on the AgNP surface, enhancing uniform particle size and diminishing aggregation propensity [5]. Citrus hystrix extract serves as an environmentally benign capping agent, offering supplementary active molecules that enhance the applicability of AgNPs in specific domains, including antimicrobials and catalysts.

The plentiful presence of lime in tropical areas, particularly in Southeast Asia, renders it a desirable raw material. Limau kuits are a significant component of the agricultural system and are frequently utilized in the food, cosmetics, and traditional medicine sectors. Nonetheless, lime peel is frequently seen as waste devoid of any intrinsic use. Incorporating lime peel waste into nanoparticle synthesis addresses agricultural waste management issues while simultaneously enhancing value for the nanotechnology sector [6].

The utilization of AgNPs synthesized from Citrus hystrix extract holds significant potential. In waste treatment, AgNPs can be employed to eradicate organic contaminants, including textile colors and pharmaceutical chemicals that are challenging to degrade. The antibacterial properties of AgNPs facilitate their application in water treatment to eradicate hazardous pathogenic microorganisms. Moreover, its catalytic characteristics facilitate the breakdown of hazardous chemical molecules into more ecologically benign products [7]. Citrus hystrix-based silver nanoparticles have proven efficient against several pathogens, including antibiotic-resistant bacteria, in the field of biomedicine. This creates prospects for the advancement of safer and more sustainable medical devices and antimicrobial materials [8].

In the domain of electronics and sensors, AgNPs derived from Citrus hystrix extract exhibit significant potential owing to their chemical and thermal stability. Silver nanoparticles (AgNPs) can detect specific chemical substances in minimal quantities through highly sensitive optical sensors. The consistency of particle size and distribution achieved using the lime extract-based technique enhances the efficacy of small electronic devices, including touch screens and transparent conductors [9].

Although extensive study has been undertaken to investigate the application of plant extracts in nanoparticle synthesis, the particular potential of Citrus hystrix as a capping agent is yet inadequately examined. Lime's distinctive bioactive composition and plentiful availability present a significant promise for the advancement of sustainable nanoparticle production. Additional research is required to elucidate the precise interactions between the bioactive components of lime and silver ions during nanoparticle production. Additionally, the optimization of the synthesis process, including extract concentration, pH, and temperature, requires investigation to guarantee the quality of the created nanoparticles [10].

This review seeks to investigate the efficacy of Citrus hystrix extract as a capping agent in the synthesis of eco-friendly AgNPs. This article aims to elucidate the function of lime in nanotechnology by examining its bioactive components, synthesis techniques, and pertinent applications, hence facilitating future advancements. This strategy positions Citrus hystrix as a viable solution for environmentally friendly nanoparticle production while connecting nanotechnology to global sustainability concepts.

1. Extraction of secondary metabolite from Citrus hystrix peel

1.1. Extraction methodology

The extraction of secondary metabolites from the peel of limau kuit (Citrus hystrix) has garnered attention in recent years due to the diverse health advantages and industrial applications of its bioactive components. Citrus hystrix peel contains abundant chemicals, including flavonoids, polyphenols, alkaloids, and essential oils, which confer notable pharmacological advantages, such as antioxidant, antibacterial, and anticancer effects [11]. This approach for extracting secondary metabolites seeks to optimize the recovery of these substances efficiently and sustainably. This article will examine different extraction techniques employed to procure secondary metabolites from lime peel, along with their respective advantages and limitations.

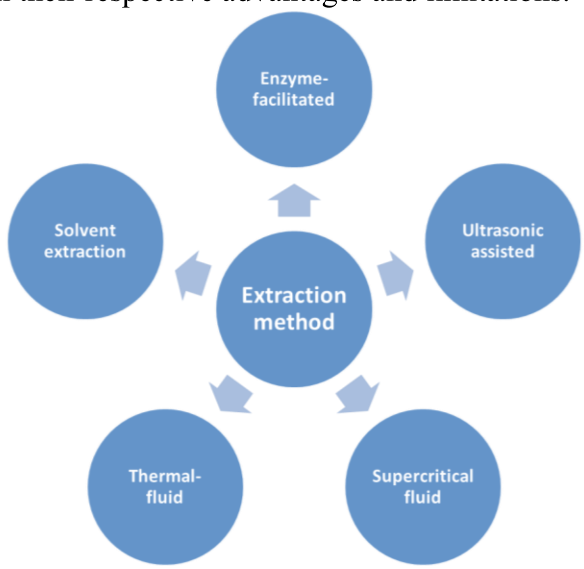


Figure 1. Extraction method of secondary metabolites from Citrus hystrix peel

Solvent extraction technique

The solvent extraction technique is among the most prevalent ways for isolating bioactive chemicals from botanical sources. This procedure utilizes organic solvents like ethanol, methanol, or ethyl acetate to extract the active chemicals present in Citrus hystrix peel. This technique has demonstrated efficacy in isolating flavonoids and polyphenols, the primary categories of secondary metabolites in Citrus hystrix peel. Additionally, organic solvents may be employed to extract the essential oils present in the skin of this fruit. Numerous studies indicate that ethanol serves as a superior solvent relative to alternatives, yielding greater extraction quantities and enhanced biological activity [12]. This approach offers ease of application and scalability; yet, it raises concerns over the usage of environmentally and health-hazardous organic solvents.

Thermal fluid extraction

Hot water extraction is a more environmentally sustainable and safer technique than extraction with organic solvents. Hot water can extract polyphenols and flavonoids from Citrus hystrix peel, which exhibits significant antioxidant activity. While this approach may lack efficiency compared to solvent methods in certain aspects, hot water extraction can yield active molecules that exhibit greater stability and enhanced acceptance for biomedical and cosmetic applications. The extraction temperature should range from 60 to 90 °C to prevent harm to heat-sensitive bioactive molecules [13]. A primary disadvantage of this approach is its inferior extraction yield relative to solvent extraction; yet, it offers promise for larger-scale production at reduced prices.

Supercritical fluid extraction

The extraction of bioactive chemicals from plants, such as Citrus hystrix peel, using supercritical fluids, particularly carbon dioxide (CO2), has emerged as a promising technique in recent years. This approach offers significant benefits regarding environmental sustainability, as CO2 is non-toxic and readily convertible into gas following the extraction procedure. Supercritical CO2 has demonstrated efficacy in extracting essential oils and non-polar molecules from the fruit's skin [14]. The primary benefit of this approach is its capacity to yield highly pure extracts devoid of solvent residue. Nonetheless, substantial initial expenses for equipment and operational circumstances necessitating extremely high pressures and temperatures pose significant difficulties to the industrial-scale use of this technology.

Ultrasonic-assisted extraction

Ultrasonic wave-assisted extraction is a novel technique that employs high-frequency sound waves to enhance solvent infiltration into plant tissue, hence improving extraction efficiency. This technique is applicable with diverse solvents, both organic and aqueous, and may extract numerous bioactive chemicals from Citrus hystrix peel, including flavonoids and essential oils.The application of ultrasonics in extraction offers benefits such as decreased processing durations, enhanced efficiency, and minimized solvent consumption. Nonetheless, while this process is more environmentally sustainable, the necessary equipment can be costly and demands meticulous handling to prevent harm to the delicate chemical [15].

Enzyme-facilitated extraction

The enzymatic extraction method employs enzymes to decompose cellulose and other plant constituents, facilitating the release of bioactive substances encapsulated inside cells. This extraction can be performed with specialized enzymes that degrade cell walls and enhance the accessibility of substances like flavonoids. This approach, while more selective and environmentally sustainable, may be constrained in commercial applications due to the expense of the enzymes and the necessity for ideal conditions for enzyme activation [16].

Each extraction method possesses distinct advantages and disadvantages, contingent upon the intended purpose and application of the target compound. Solvent extraction techniques yield greater outputs, although may pose health and environmental hazards. Hot water extraction and enzymatic methods are more environmentally sustainable. However, they may exhibit reduced efficiency in certain instances. The application of supercritical CO2 with ultrasonic help demonstrates significant potential for enhancing yield and extraction efficiency; nevertheless, cost and equipment variables are major considerations. The rising demand for eco-friendly natural active ingredients will drive the ongoing development and optimization of this extraction technology, creating prospects for the broader application of lime peel across many industries.

1.2. Principal constituent of Citrus hystrix extract

Limau kuit extract (Citrus hystrix) has many secondary metabolites that may serve as active components in multiple applications, including as a capping agent in the manufacture of silver nanoparticles (AgNPs). These secondary metabolites include flavonoids, polyphenols, alkaloids, essential oils, and terpenoids, all of which contribute significantly to the stability and bioactivity of AgNPs. The extraction method employed to get this metabolite influences both the composition and quantity of the chemical, thereby impacting its efficacy as a capping agent.

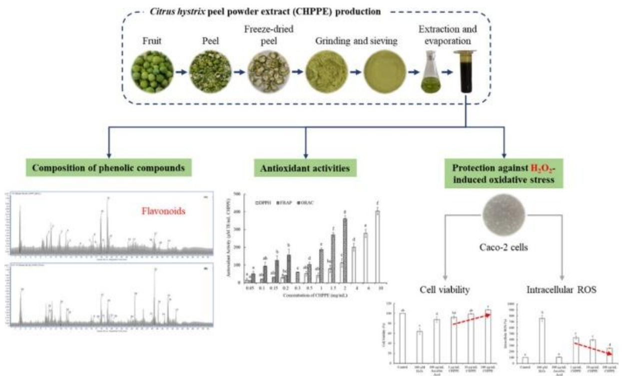


Figure 2. Main constituent of Citrus hystrix peel extract and its antioxidant activities [22]

Solvent extraction techniques, including ethanol, methanol, and ethyl acetate, have demonstrated efficacy in extracting flavonoids and polyphenols from Citrus hystrix peel. Flavonoids, including kaempferol, quercetin, and rutin, are present in elevated amounts in the ethanol extract of Citrus hystrix peel [17]. This flavonoid molecule acts as a reducing agent, converting silver ions into silver nanoparticles, and serves as a capping agent on the surface of AgNPs to inhibit agglomeration and enhance particle stability [18]. In addition to flavonoids, the polyphenols included in lime peel extract exhibit antioxidant properties that may mitigate nanoparticle peroxidation and preserve their structural integrity.

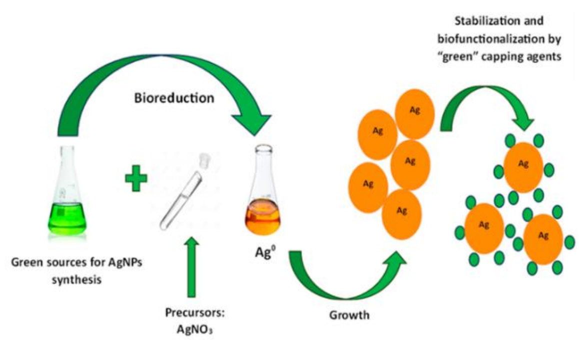
The extraction of hot water yields several secondary metabolites that may serve as capping agents. Moolsup [19] found that hot water extract from Citrus hystrix peel contains many polyphenols and flavonoids, but at lower quantities than those found in organic solvent extracts. Nonetheless, hot water extraction offers the benefit of enhanced purity and a reduced risk associated with hazardous solvents. The chemicals derived from this technique serve as capping agents, stabilizing AgNPs while imparting antibacterial and antioxidant properties used in biological applications and waste management.

Essential oil derived from Citrus hystrix peel, obtainable via steam extraction or solvent methods like ethanol, include terpenoid components such as limonene and citral, which may serve as capping agents in the synthesis of AgNPs. Mustapha [20] indicates that terpenoids in lime peel essential oil can enhance the preservation of silver nanoparticles' surfaces, acting as a physical barrier that inhibits particle aggregation. Moreover, terpenoids have significant biocompatibility, rendering them an optimal selection for biomedical and sensor applications. The efficacy of this terpenoid is augmented by research indicating that lime peel essential oil exhibits antibacterial and anti-inflammatory properties, thereby facilitating the effective utilization of AgNPs coated with lime peel extract in waste management and medical applications.

Ultrasonic-assisted extraction can be employed to extract secondary metabolites with enhanced efficiency. Vo [21] shown that this approach enhances the extraction yield of flavonoids and polyphenols, hence facilitating the synthesis of AgNPs. This method facilitates the utilization of reduced solvent quantities, hence diminishing environmental repercussions and enhancing the sustainability of the extraction procedure.

2. Synthesis of silver nanoparticles utilizing a flavonoid-based capping agent

The manufacture of silver nanoparticles (AgNPs) utilizing lime peel extract (Citrus hystrix) as a capping agent demonstrates enhanced control over particle size and morphology, benefiting biomedical, sensing, and waste processing applications. Flavonoids, polyphenols, and terpenoids in Citrus hystrix peel extract serve as efficient reducing and protecting agents, yielding AgNPs with consistent particle sizes and narrow distribution. Research indicates that AgNPs synthesized from lime peel extract exhibit sizes between 12 and 30 nm, characterized by a limited size distribution and spheroidal form [23]. The results demonstrate that Citrus hystrix extract can generate smaller silver nanoparticles in comparison to several other plant extracts utilized as



capping agents.

Figure 3. Mechanism of AgNPs synthesis using flavonoid-based capping agent [24]

The process of synthesizing AgNPs with Citrus hystrix peel extract, rich in flavonoids and polyphenols, also influences the size and morphology of the resultant nanoparticles. This molecule serves as a reducing agent and stabilizes nanoparticles by creating a capping layer that inhibits particle aggregation. Consequently, Citrus hystrix peel extract is excellent in generating tiny nanoparticles and ensuring the long-term stability of AgNPs.

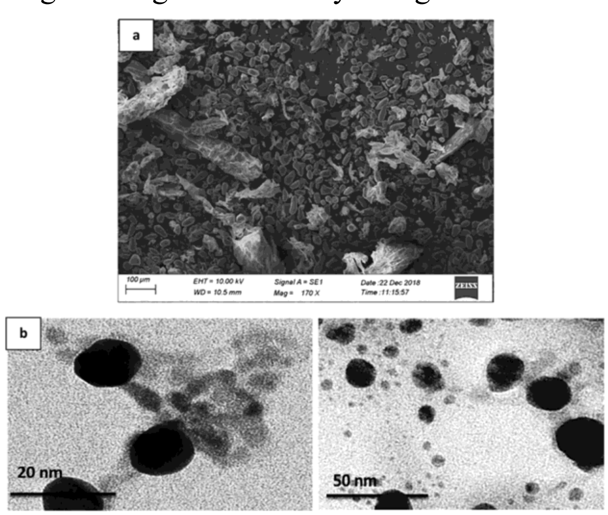


Figure 4. (a) Morphology and (b) TEM image of AgNPs synthesized using flavonoid as capping

agent [25]

The synthesis of AgNPs utilizing flavonoid as the main compound of capping agent demonstrates significant potential for generating nanoparticles characterized by tiny size, narrow distribution, and consistent shape as introduced in Fig 4a and 4b. The scanning electron microscopy (SEM) image in Figure 4(a) illustrates the surface morphology of silver nanoparticles (AgNPs) synthesized using flavonoid as a capping agent. The nanoparticles appear to be well-dispersed with irregularly shaped agglomerates, which could be attributed to the interaction between AgNPs and the flavonoid molecules. The presence of larger structures may indicate partial aggregation of the nanoparticles due to secondary interactions. The SEM image also suggests a relatively uniform distribution of the particles, highlighting the potential role of flavonoids in stabilizing the nanoparticles and preventing excessive agglomeration.

The transmission electron microscopy (TEM) images in Figures 4(b) provide a more detailed view of the AgNPs at the nanoscale. The nanoparticles exhibit spherical to quasi-spherical shapes with a size range below 50 nm. The variation in particle size might be due to the influence of flavonoids, which can act as both reducing and stabilizing agents during the synthesis process. The darker contrast of some particles suggests a higher electron density, confirming the presence of AgNPs. The observed particle size distribution indicates that the flavonoid capping effectively controls nanoparticle growth, leading to a relatively uniform morphology.

The benefits render AgNPs for various application such as waste management, biomedicine, and sensor technology. Additional study is required to refine synthesis conditions and investigate its possible applications more extensively.

3. Application of Ag nanoparticles to promote sustainability

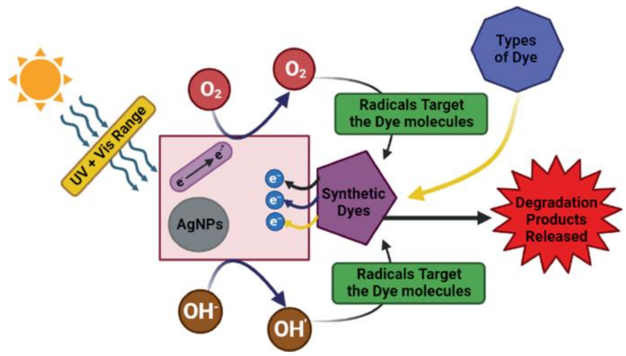
3.1. Wastewater treatment

Silver nanoparticles (AgNPs) have garnered significant interest in wastewater treatment owing to their distinctive physicochemical characteristics, including elevated surface area, antibacterial efficacy, and capacity to enhance chemical reactions. These characteristics render AgNPs an exceptional alternative for environmental remediation, especially in the treatment of industrial and hazardous waste. Numerous research have evidenced the efficacy of AgNPs in eliminating contaminants from wastewater, including heavy metals, organic pollutants, and microbes.

The primary mechanism enabling AgNPs to effectively treat waste is their extensive surface area, facilitating efficient pollutant adsorption. AgNPs have demonstrated efficacy in adsorbing heavy metals, including lead (Pb), cadmium (Cd), and mercury (Hg), from polluted water. The adsorption capability of AgNPs is attributable to their extensive surface area and the presence of surface functional groups, such as hydroxyl and amino, which interact with metal ions [26–28]. This interaction leads to the accumulation of metal ions on the surface of AgNPs, subsequently extracting the metal from the water. The AgNps also can be used as plasmonic material to enhanced photocatalytic performance of metal oxide-based photocatalyst, it was promising for wastewater treatment via advanced oxidative process (AOP) [29,30].

Furthermore, AgNPs possess potent antibacterial activities, which may be advantageous in addressing biological pollutants in wastewater. The efficacy of AgNPs in suppressing the proliferation of bacteria and other microbes has been extensively researched across multiple situations. In wastewater treatment, AgNPs facilitate the eradication of pathogenic microbes, hence enhancing overall water quality. AgNPs have demonstrated efficacy in diminishing bacterial populations in contaminated water by compromising bacterial cell membranes and obstructing cellular functions. AgNPs serve as an efficacious agent for mitigating microbial contamination in wastewater, particularly within the food and pharmaceutical sectors, where hygiene and sanitation are paramount [31].

Numerous research have investigated the efficacy of AgNPs in eliminating organic contaminants from wastewater. Silver nanoparticles (AgNPs) can function as catalysts in the breakdown of organic molecules, transforming contaminants into less hazardous chemicals. For instance, AgNPs have been employed to mitigate detrimental organic dyes like methylene blue and rhodamine B, commonly present in textile industry effluents. The elevated catalytic activity of AgNPs is thought to stem from their capacity to promote electron transfer processes, resulting in the degradation of complex organic compounds [32], as illustrated in Fig 5. Furthermore, AgNPs demonstrate potential in the breakdown of pharmaceutical pollutants, which are progressively emerging as



contaminants in wastewater.

Figure 5. The role AgNPs for wastewater treatment [33]

A notable advantage of AgNPs in liquid waste treatment is their capacity to enhance efficiency when combined with other materials. For instance, AgNPs have been integrated into composite materials, including activated carbon and polymer membranes, to enhance their adsorption and filtration efficacy. A study demonstrated the incorporation of AgNPs onto a graphene oxide (GO) platform to improve the elimination of heavy metals and organic contaminants from contaminated water [34]. This composite material demonstrated enhanced adsorption and catalytic properties relative to AgNPs alone, suggesting a possible synergistic effect in wastewater treatment.

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3.2. Biomedical application

Silver nanoparticles (AgNPs) possess significant potential in biological applications due to their antimicrobial, antibacterial, and biocompatible properties. Numerous research indicate that AgNPs are applicable in illness treatment, infection prevention, and as therapeutic agents for cancer management. The efficacy of AgNPs as a therapeutic agent in the medical field is significantly influenced by the size, shape, and dispersion of the nanoparticles, which affect their interactions with cells and bodily tissues.

The antibacterial characteristics of AgNPs have emerged as a primary emphasis in the advancement of biomedical products, including topical medications, wound dressings, and medical implants. Gouyau [35] demonstrate that AgNPs exhibit significant antibacterial efficacy against many pathogens, including Escherichia coli and Staphylococcus aureus, commonly associated with nosocomial infections. These characteristics render AgNPs a crucial agent in the prevention of infections in wounds and medical implants. AgNPs function by compromising bacterial cell membranes, interfering with cellular metabolism, and inducing oxidative stress, ultimately leading to bacterial cell death. A study conducted by Mateo [36] demonstrated that AgNPs can mitigate antibiotic resistance, a pervasive issue in the management of bacterial infections.

In oncology, AgNPs have been investigated as therapeutic agents for both localized and systemic cancer treatment. AgNPs serve as drug delivery agents, capable of transporting chemotherapeutic medications directly to cancer cells by leveraging their modifiable features to identify specific targets on the cancer cell surface. Silver nanoparticles (AgNPs) can function as photothermal agents, absorbing near-infrared light to produce heat that eradicates cancer cells while preserving adjacent healthy tissue. Kovacs [37] demonstrated that AgNPs enhance cancer treatment by augmenting the concentration of chemotherapeutic agents at the tumor location and mitigating the adverse effects of conventional therapy.

Moreover, AgNPs are utilized in diagnostic applications, including medical imaging and biomarker identification. Silver nanoparticles (AgNPs) serve as contrast agents in magnetic resonance imaging (MRI) and optical imaging to enhance image resolution and augment detection sensitivity. AgNPs may be conjugated with dyes or biomolecules that facilitate selective binding to biomarkers or target cells, hence enhancing the precision of disease detection. Takallu [38] shown that AgNPs combined with DNA oligonucleotides enable the swift detection of specific pathogens in blood or other bodily fluids, hence aiding speedy and accurate diagnosis.

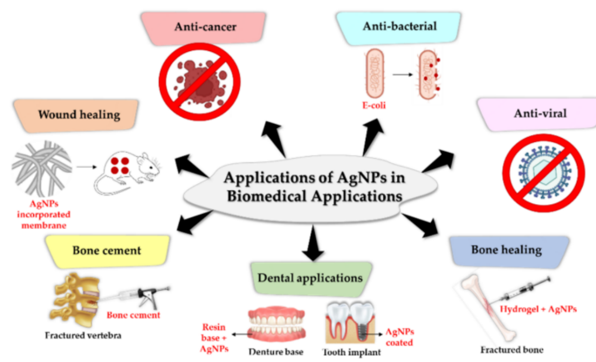

Figure 6. The role AgNPs in biomedical application [39]

Despite the numerous advantages of AgNPs in biomedical applications, certain problems must be addressed. A primary worry is the potential toxicity of AgNPs to healthy cells, particularly at elevated levels or with prolonged exposure. Numerous studies indicate that AgNPs can inflict harm on human cells and tissues by generating free radicals that induce oxidative stress. To mitigate toxicity, strategies such as the surface modification of nanoparticles with biocompatible substances or the utilization of AgNPs in composite forms with other safer materials are being investigated. Research by [40] demonstrated that AgNPs encapsulated in polymer or cellulose films can mitigate their harmful effects on human cells while preserving their efficacy as antibacterial agents.

Furthermore, comprehending the long-term effects of employing AgNPs in medicinal applications is crucial. Additional investigation is required to assess the potential accumulation of nanoparticles within the body and their impact on human health. Certain studies indicate that AgNPs may concentrate in specific organs, including the liver and kidneys, potentially leading to adverse biological effects upon repeated exposure.

AgNPs present extensive promise in biomedical applications, serving as therapeutic, diagnostic, and infection prevention agents. Despite ongoing concerns over nanoparticle toxicity and accumulation, advancements in nanoparticle modification and formulation techniques are anticipated to address these issues. With continued study and development, AgNPs can significantly advance the biomedical area, offering unique solutions for illness treatment and healthcare.

3.3. Electronics and sensors

Silver nanoparticles (AgNPs) have garnered significant interest in electronics and sensor applications due to their electrical conductivity, stability, and capacity to detect diverse biomolecules or pollutants. AgNPs, owing to their nanoscale dimensions, demonstrate superior optical and electrical characteristics relative to bulk silver. They are utilized in diverse electronic devices, including gas sensors, biosensors, energy storage systems, and nano-based detecting applications.

In the realm of sensors, AgNPs are frequently utilized as materials for the creation of gas sensors and biomolecular sensors. Silver nanoparticles (AgNPs) can function as superior coupling agents in resistance and capacitance-based sensors, enabling the monitoring of resistance or capacitance alterations upon interaction with certain gasses or biomolecules. Zahran [41] reported utilizing AgNPs modified with various materials in gas sensors for the detection of ammonia and nitroglycerin, demonstrating a rapid and sensitive response. The exceptional conductivity and capacity of AgNPs to engage with diverse gases render them optimal for detecting environmental pollutants like NO2, CO, and H2S, frequently employed in air quality monitoring applications.

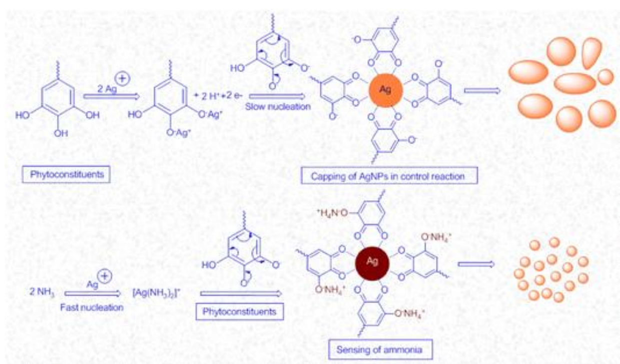

Figure 7. The role AgNPs in ammonia detection [42]

Furthermore, AgNPs have been utilized in biosensors for the swift identification of illnesses or biomarkers. For instance, AgNPs functionalized with DNA or antibodies are employed in the creation of sensors for the detection of specific infections or disease biomarkers. Danai [43] demonstrated that AgNPs function as a platform for the attachment of specific oligonucleotides, facilitating the swift detection of target DNA in biological specimens. The use of AgNPs in these biosensors significantly enhances detection sensitivity and selectivity, which is crucial for medical and diagnostic applications.

Nonetheless, the implementation of AgNPs in electronics and sensor technologies encounters obstacles related to toxicity and long-term stability. Sroysee [44] indicate that while AgNPs exhibit superior efficacy in gas and biosensors, the possible accumulation of nanoparticles in devices and its implications for human health warrant consideration. Consequently, additional study is required to enhance the stability and safety of AgNPs, particularly for prolonged use.

AgNPs demonstrate significant potential in electrical and sensor applications. They are applicable in numerous technologies, including gas sensors, biosensors, energy storage systems, and flexible electronic devices. Despite ongoing concerns related to toxicity and stability, advancements in the design and modification of AgNPs are anticipated to surmount these issues and facilitate additional applications in the electronics and sensor sectors.

4. Conclusion

The extraction of secondary metabolites from Citrus hystrix peel demonstrates significant promise in the manufacture of silver nanoparticles (AgNPs) as a capping agent, which is crucial in regulating the size and stability of the nanoparticles. Maceration and ultrasonication are excellent extraction procedures for creating bioactive compounds that inhibit AgNPs agglomeration, therefore enhancing the quality and performance of the resultant nanoparticles. The synthesis of AgNPs using lime extract yields nanoparticles measuring approximately 10-50 nm, exhibiting a uniform and stable shape.

In waste treatment applications, AgNPs exhibit the capacity to adsorb contaminants or participate in redox reactions, offering an eco-friendly approach for the remediation of contaminated water or soil. In the biomedical sector, AgNPs are utilized as antibacterial agents and in drug delivery systems due to their biocompatibility and efficacy in combating infections. In electronics and sensor applications, AgNPs are utilized in gas sensors, biosensors, and energy storage devices, providing excellent electrical conductivity and versatility in the creation of innovative electronic systems.

Nonetheless, the primary hurdles in the utilization of AgNPs are concerns regarding long-term stability and probable toxicity. Consequently, additional research is required to elucidate the interaction mechanism between lime peel extract and Ag+, as well as to refine the synthesis procedure for the more efficient and safe production of AgNPs. In summary, AgNPs produced from lime peel extract present a compelling and eco-friendly option for several applications, demonstrating significant potential in waste management, biomedicine, and the electronics and sensor sectors.

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