Nanotechnology in action: silver nanoparticles for improved environmental remediation (#100296)

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Nanotechnology in action: silver nanoparticles for improved environmental remediation

Suresh Babu Naidu Krishna Corresp., [1, 2] , **Abdul Gaffar Sheik** [2] , **Karen Pillay** [3] , **Manhal Ahmed Hamza** [4] , **Mohammed Elamir** [5] , **Samy Selim** Corresp. [5]

[1] Faculty of Health Sciences, Durban University of Technology, Durban, KwaZulu-Natal, South Africa

[2] Institute for Water and Wastewater Technology, Durban University of Technology, Durban, KwaZulu-Natal, South Africa

[3] Department of Biochemistry, School of Life Sciences, Westville campus, University of KwaZulu-Natal, Durban, South Africa

[4] Department of Medical Microbiology, Faculty of Medical Laboratory Sciences, Omdurman Islamic University, Omdurman 14415, Sudan, Omdurman Islamic University, Omdurman, Sudan

[5] Department of Clinical Laboratory Sciences, College of Applied Medical Sciences, Jouf University, Sakaka, Saudi Arabia, Jouf University, Sakaka, Saudi Arabia

Corresponding Authors: Suresh Babu Naidu Krishna, Samy Selim
Email address: Sureshk@dut.ac.za, sabdulsalam@ju.edu.sa

The emergence of nanoscience revolutionized the scientific landscape and redirected research efforts. Today, the world is immersed in nanotechnology and nanoparticles (NPs), which possess diverse applications in every sphere of life, including environmental realms. Numerous nanoparticles have been synthesized and extensively utilized, captivating researchers worldwide. Among these, silver nanoparticles (AgNPs) stand out due to their cost-effectiveness and abundant presence in the earth's crust, making them a compelling subject for further exploration. This comprehensive review delves into the role of silver nanoparticles in environmental remediation, emphasizing their critical efficacy in addressing environmental challenges. Leveraging the distinctive properties of AgNPs, such as their antibacterial and catalytic characteristics, innovative solutions for efficient treatment of pollutants are being developed. The review critically examines the transformative potential of silver nanoparticles, exploring their various applications and promising achievements in enhancing environmental remediation techniques. As environmental defenders, this paper advocates for intensified investigation and application of silver nanoparticles.

Nanotechnology in Action: Silver Nanoparticles for Improved Environmental Remediation

Suresh Babu Naidu Krishna[1*], Abdul Gafar Sheik [1], Karen Pillay [2], Manhal Ahmed Hamza [3], Mohammed Yagoub Mohammed Elamir [4], Samy Selim [4*]

[1] Institute for Water and Wastewater Technology, Durban University of Technology, PO Box 1334, Durban-4000, South Africa. Email: abduls@dut.ac.za

[2] School of Life Sciences, University of KwaZulu-Natal, Private Bag X54001, Westville campus, Durban 4001, South Africa. Email: muthusamy@ukzn.ac.za

[3] Department of Medical Microbiology, Faculty of Medical Laboratory Sciences, Omdurman Islamic University, Omdurman 14415, Sudan. Email: manhalo26ahb@oiu.edu.sd

[4] Department of Clinical Laboratory Sciences, College of Applied Medical Sciences, Jouf University, Sakaka, Saudi Arabia. Email: myelamir@ju.edu.sa

Corresponding Author:

Suresh Babu Naidu Krishna[1], Samy Selim[4]

[1] Institute for Water and Wastewater Technology, Durban University of Technology, PO Box 1334, Durban-4000, South Africa. Email: sureshk@dut.ac.za

[4] Department of Clinical Laboratory Sciences, College of Applied Medical Sciences, Jouf University, Sakaka, Saudi Arabia

Email address: sabdulsalam@ju.edu.sa

Abstract

The emergence of nanoscience revolutionized the scientific landscape and redirected research efforts. Today, the world is immersed in nanotechnology and nanoparticles (NPs), which possess diverse applications in every sphere of life, including environmental realms. Numerous nanoparticles have been synthesized and extensively utilized, captivating researchers worldwide. Among these, silver nanoparticles (AgNPs) stand out due to their cost-effectiveness and abundant presence in the earth's crust, making them a compelling subject for further exploration. This comprehensive review delves into the role of silver nanoparticles in environmental remediation, emphasizing their critical efficacy in addressing environmental challenges. Leveraging the distinctive properties of AgNPs, such as their antibacterial and catalytic characteristics, innovative solutions for efficient treatment of pollutants are being developed. The review critically examines the transformative potential of silver nanoparticles, exploring their various applications and promising achievements in enhancing environmental remediation techniques. As environmental defenders, this paper advocates for intensified investigation and application of silver nanoparticles.

Keywords: Biogenic, Environment, Nanoscience, Remediation, Silver nanoparticles, antimicrobial activity, water treatment

Introduction

Environmental pollution is a major global dilemma that is progressively worsening and causing serious and irreversible damage to the planet (Das et al. 2015; Ortúzar et al. 2022). Urbanization and the ever-growing human population have pushed the limits of resource use, which eventually contributes to the deterioration of nature. Carbon monoxide, chlorofluorocarbons, volatile organic compounds, hydrocarbons, and nitrogen oxides are only few of the many pollutants that are found in the air today, along with several others(Feizi et al. 2023; Rani et al. 2023; Turdimovich & Khasanovich 2023). Arsenic, heavy metals, and chlorinated chemicals pollute the water and soil. Some of the major causes of water and soil degradation are sewage, industrial effluents, indiscriminate use of pesticides and fertilizers, and oil spills (Elbadawy et al. 2023; Usman et al. 2020).

Nanomaterials are materials with unique qualities at the nanoscale, have attracted a lot of interest because of their unique physical, chemical, and mechanical capabilities (El-Saadony et al. 2023; Ngcongco et al. 2023a; Ngcongco et al. 2023b). The increased surface area-to-volume ratio of nanoparticles improves their reactivity and adsorption capability (Kumari et al. 2019; Shankara et al. 2022). This property enables nanoparticles to effectively remove pollutants and contaminants such as heavy metals, organic compounds, and even pathogens from wastewater. For example, iron oxide nanoparticles have been shown to be effective in the removal of heavy metals via adsorption and coagulation processes(Jabbar et al. 2022). Carbon-based nanomaterials, such as activated carbon nanotubes and graphene oxide, have high adsorption capacities, making them useful for removing organic contaminants and colours (Amil Usmani et al. 2017; Joy et al. 2023; Kosgey et al. 2022). Furthermore, metal oxide nanoparticles such as titanium dioxide and zinc oxide have photocatalytic characteristics that allow the breakdown of organic contaminants when exposed to ultraviolet (UV) light (Pal et al. 2022; Prakash et al. 2022). Nanomaterials are a promising new technology for environmental remediation, and further research is needed to explore their full potential.

Silver nanoparticles (AgNPs) are highly distinctive and appealing due to their low cost of manufacturing, environmental sustainability, and, most outstandingly, their high toxicity primarily to multidrug-resistant microorganisms only rather than healthy cells at low dosages(Nie et al. 2023). As a result, it now has a multifaceted application (Guerra et al. 2018; Mo et al. 2022a; Nakamura et al. 2019; Ngcongco et al. 2023b). Because of their many beneficial features, silver nanoparticles have the potential to be effective antibacterial agents and plasmonic NPs for use in environmental applications(Tarrat & Loffreda 2023). For instance, the formation of reactive oxygen species (ROS), surface plasmon resonance (SPR), and specific reaction selectivity are all made possible using AgNPs. Indeed, AgNPs-based nanomaterials with their antibacterial, optical, and electrical properties are at the forefront of nanotechnology, with applications in environmental disinfection, pollutant elimination, environmental monitoring, and energy conversion (Del Prado-Audelo et al. 2021; Durgalakshmi et al. 2019; Gracia-Pinilla et al. 2008; Khin et al. 2012; Mo et al. 2022b; Ningthoujam et al. 2022). Considering the safe and biocompatible nature of the AgNPs, it becomes worthy to apply it to environment remediation purposes in the form of electro sensors, photocatalysts, and fluorogenic probes(Abraham et al. 2013; Bourgonje et al. 2023) .

This review highlights advanced environmental remediation applications and fundamental principles to guide future research on AgNPs integrated functional materials. Furthermore, it discusses silver nanoparticle uses like electro sensors, photocatalysts, and fluorogenic probes.

Methodology

Various scientific databases, including PubMed, Google Scholar, Web of Science, and others, are employed to conduct literature searches. The search is performed by utilizing different combinations of keywords that are relevant to the topic. Most of these publications have been published in the fields of chemistry, materials science, physics, engineering, polymer science, spectroscopy, electrochemistry, molecular biochemistry, optics, and spectroscopy (Tran & Le 2013). Precise criteria for inclusion and exclusion are established to determine which studies should be considered. These criteria may include factors such as the study's methodology, the publication year, and the research's main area of interest. The titles and abstracts of the identified studies are examined to determine if they satisfy the inclusion criteria. A comprehensive analysis is conducted on the complete text of the chosen papers. Studies that do not match the inclusion criteria are excluded at this stage. Data that is pertinent is retrieved from the studies that are provided. This may encompass aspects such as the research methodology, the size of the sample, the primary discoveries, and so on. The evaluation of the studies' quality is conducted utilizing suitable methodologies (Magdy et al. 2024). Studies of low quality are skipped.

Biosynthesis of silver nanoparticles

Conventional strategies versus biological synthetic strategies

Metallic silver is a soft, white, shiny rare element that is naturally available and has good thermal and electrical conductivity(Islam et al. 2021; Nie et al. 2023). Silver nanoparticles are a type of metallic silver that is less than 100 nm in at least one dimension, enabling the nanoparticles a high surface area to volume ratio(Antunes et al. 2017). Current methodologies for AgNP synthesis and other metal preparations can be divided into two categories: "top to bottom," which is typically used by physicists, and "bottom to up", which is commonly used by chemists (Mo et al. 2022b; Moodley et al. 2018). Both approaches converge on the nanodimension, but their synthetic technologies are very different from one another. In "top to bottom" procedures, several physical methods are used to break down bulk solid materials into their nanoparticulate form. These physical methods include grinding, milling, sputtering, evaporation-condensation, and thermal/laser ablation, among others. "Bottom to up" procedures involve a variety of chemical and biological processes to produce nanoparticles via the self-assembly of atoms such as Ag^{+} into nuclei, which then evolve into nano-sized particles. These processes are known as "bottom to up" synthesis. Techniques such as evaporation-condensation and laser ablation are two important physical approaches that can be used to create nanoparticles in a "top to bottom" fashion [14]. Evaporation condensation is accomplished using a tube furnace operating at room temperature, with the primary material (metal Ag) contained in a boat that is positioned in the middle of the furnace and vaporized into a carrier gas (Ahmed et al. 2016). This method has been shown to have a few flaws, such as the fact that the furnace takes up a considerable amount of room, necessitates a significant amount of energy to raise the temperature of the atmosphere surrounding the source material, and necessitates a significant amount of time to achieve thermal stability. However, one of the most significant drawbacks of this method of synthesis is that it produces defects in the surface structure of the nanoparticles that are produced, which, in the end, can change the physical characteristics of the nanoparticles (Iravani et al. 2014; Sportelli et al. 2018).

Irradiation is utilized in the process of laser ablation to strip material away from a bulk metal that is in solution. The efficacy of this method and the features of the nascent particles are substantially determined by a variety of parameters. These parameters include the wavelength of the laser, the duration of laser pulses, the laser fluence, the ablation time, and the effective liquid medium with or without surfactants(Chen & Yeh 2002; Kim et al. 2005). The elimination of contaminants in solution that have the potential to contaminate the nanoparticle preparation is a significant benefit that can be gained from using laser ablation for the preparation of AgNP(Tsuji et al. 2002).

Wet chemical reduction is the method for the manufacture of nanoparticles that is used most frequently (Iravani et al. 2014), despite the fact that various other ways have been documented (Amin et al. 2009; Yang & Pan 2012). This method is part of the "bottom-to-up" strategy. Wet chemical reduction is exactly what it sounds like it is. It involves the reduction of a metal salt precursor in an organic or aqueous solution. Ascorbate, borohydride, citrate, elemental hydrogen, formaldehyde, N-N-dimethyl formamide (DMF), Tollen's reagent, and polyethylene glycol blocks are some of the organic and inorganic chemicals that have been successfully utilized as reducing agents in the production of AgNPs(Bagheri et al. 2023; Iravani 2011; Thangavelu et al. 2022). Other reducing agents include borohydride, citrate, and formaldehyde. In order to stop the formation of aggregates of newly formed nanoparticles, the reaction solution contains, in addition to reducing agents, protective stabilizing agents (Bai et al. 2007; Kapoor et al. 1994). Once stability is reached, this approach has the potential to be effective in producing high yields of nanoparticles while maintaining low costs of preparation (Song et al. 2009). Nevertheless, the effectiveness of this technology is called into question due to the possibility of nascent nanoparticles being contaminated by precursor chemicals, the utilization of hazardous solvents, and the production of risky by-products(Iravani et al. 2014; Thakkar et al. 2010).

It should come as no surprise that the physical and chemical approaches both have some shortcomings that prevent them from being utilized in the process of preparing nanoparticles for use in biological applications(Nie et al. 2023; Panda et al. 2023). In this context, substantial attempts have been made to develop nanoparticle synthesis processes that are not harmful to the environment. In its most basic form, this would involve the application of non-harmful biotechnological instruments, which is essentially what gave rise to the idea of green technology. The easiest way to explain this technology is to think of it as the synthesis of nanoparticles by the utilization of biological pathways, such as plants and microbes, or the byproducts of those biological pathways (Joy et al. 2023; Radwan et al. 2021; Thangavelu et al. 2022). These bio-inspired approaches (Figure 1) are not only friendly to the environment, but they are also economical and simple to scale up for use in big productions(Dhuper et al. 2012).

The physical and chemical approaches outlined above have limitations that hinder their implementation in the synthesis of nanoparticles for biological purposes (Islam et al. 2021). In this context, significant endeavors have been made to formulate nanoparticle synthesis methods that adhere to environmentally sustainable principles. In essence, this would involve the utilization of harmless biotechnological instruments and has led to the emergence of the notion of environmentally friendly technology. This method can be most accurately characterized as the utilization of biological pathways, specifically involving plants, microbes, or their byproducts, in the process of synthesizing nanoparticles(Patra & Baek 2015; Singh et al. 2019). The bio-inspired technologies depicted in Figure 1 exhibit not only environmental friendliness, but also cost-effectiveness and the potential for seamless expansion to accommodate large-scale manufacturing (Ahmed et al. 2016).

Figure 1. Multiple techniques of nanoparticle synthesis (Mtambo et al. 2019).

As highlighted earlier, biological methods for the synthesis of AgNP involve the utilization of living organisms or the extracts of such organisms as capping or reducing agents in a synthetic reaction. To this day, numerous types of biological entities, such as viruses(Velusamy et al. 2016), bacteria (Thakkar et al. 2010), plants (Iravani & Varma 2019), algae (Khanna et al. 2019), fungi(Joy et al. 2023), yeast (Skalickova et al. 2017), and mammalian cells (Nazarenus et al. 2014), have been investigated to determine whether or not they are capable of lowering the amount of Ag^{+}. The process underlying biological synthesis can be broken down into two distinct phases: the bioreduction phase and the biosorption phase. Bioreduction takes place when metal ions go through the process of chemical reduction and become complexes that are biologically stable. A wide variety of organisms have been seen to exhibit dissimilatory metal reduction, which involves the coupling of enzyme reduction with enzyme oxidation. The resultant nanoparticles can be safely removed from the reaction mixture when they have become stable and inert. Alternately, biosorption refers to the process of attaching metal ions onto a living entity, such as the cell wall. There are several species of bacteria, fungi, and plants, each of which can produce peptides or possess modified cell wall structures that are capable of binding metal ions and, as a result, producing stable complexes in the shape of nanoparticles (Pantidos & Horsfall 2014). To obtain a comprehensive understanding of the literature, we suggest readers consulting scholarly review articles and book chapters that have been published within the past two years (Bagheri et al. 2023; Bourgonje et al. 2023; Bruna et al. 2021; Husain et al. 2023; Jaswal & Gupta 2023; Thangavelu et al. 2022; Yaqoob et al. 2020).

Application of silver nanoparticles for the environment remediations

Silver nanoparticles as sensors

The amalgamation of nanotechnology with sensor technology has resulted in a synergy that has revolutionized environmental monitoring. By integrating AgNPs into sensors, scientists and engineers have unlocked incredible opportunities to detect and analyze environmental pollutants with unprecedented precision (Li et al. 2015). Silver nanoparticles have a wide range of applications that is of benefit to the environment.

One of these being the use of nanocomplexes as sensors for environmental pollutants (Konduri et al. 2024).

Table 1. List of silver-based nano-complexes that have shown potential as detection agents of environmental pollutants in recent years (2016-2023)

In recent study, graphite carbon sheets were utilized to create AgNPs, which are then employed as an electrochemical sensor to detect organic compounds in water samples. Extensive analysis was conducted on the developed nanomaterial using scanning electron microscopy (SEM), X-ray diffraction technique (XRD), and IR spectroscopy to examine its structure, composition, and morphology. The nitrofurazone sensor demonstrated remarkable sensitivity in detecting the substance, with 1.2×10^{-8} M for the limit of detection and 1.3×10^{-7} M for the limit of quantification. The sensor showed a reduction peak at -0.57V, and a calibration curve was created using concentrations ranging from 10^{-4} M to 2×10^{-7} M, indicating the reduction of nitrofurazone. Through experimental verification, it has been shown that the use of AgNPs on the carbon nanosheets significantly improves their electrocatalytic ability and enhances their potential for reducing nitrofurazone. The sensor performed excellently and is suitable for detecting nitrofurazone in various aqueous samples, including water from the tap, human faeces, and commercial milk. Furthermore, it demonstrated exceptional consistency and the ability to be used repeatedly (Zoubir et al. 2022).

A new study has introduced a highly accurate and efficient colorimetric technique for identifying chromium (III) in tap water (Qadri et al. 2022). This method utilizes silver nanoparticles that have been functionalized with a derivative of phenyl benzotriazole (PBT-AgNPs). At room temperature, the PBT-functionalized nanoparticles were produced through a reduction process using sodium borohydride (NaBH4). Multiple approaches were used to investigate the nanoparticles, including UV–Vis spectroscopy, Zetasizer, Fourier Transformer InfraRed (FTIR), Scanning Electron Microscope (SEM), and Atomic Force Microscopy (AFM). Despite the variations in temperature, pH, and ionic strength of the electrolytes, the stability of the nanoparticles remained largely unaffected. After conducting tests, it was discovered that the PBT-AgNPs functioned as a probe with remarkable sensitivity to the presence of Cr (III). Additionally, they exhibited exceptional selectivity when other interfering metal ions were present. The Jobs plot revealed a binding ratio of 1:2 between the nanoparticles and Cr (III). The quenching of the Surface Plasmonic Resonance (SPR) band, as the concentration varies, exhibits a highly linear response (R2 = 0.9992), with a remarkable limit of detection of 0.2 μM. Additionally, the PBT-AgNPs were utilized as a sensing probe to detect the presence of Cr (III) in tap water samples. These experimental findings demonstrate the use of supramolecular stabilized silver nanoparticles as a straightforward, precise, and convenient alternative for detecting Cr (III).

Novel sensors were developed by Zhao et al., which were modified with nano silver-gold and silver-gold oxides (Figure 2). For this study, a new electrochemical sensor array was created using modified electrodes with gold-silver nanoparticles. The goal was to detect both chromium species (Cr (III) and (VI)) simultaneously. In this study, the screen-printed carbon electrodes (SPCEs) were enhanced with silver-gold bimetallic nanoparticles using electrochemical deposition. The purpose was to detect Cr (VI) efficiently. For the detection of Cr (III), the silver-gold bimetallic nanoparticles were oxidized to create stable silver-gold bimetallic oxide nanoparticles. Based on the findings, it was observed that incorporating silver, at a theoretical value of 1% of gold, had a positive impact on the creation and maintenance of oxides on the surface of gold nanoparticles. After conducting thorough characterization, the two types of electrodes were combined to create an electrochemical sensor array capable of detecting Cr (VI) and Cr (III) with high selectivity and sensitivity. For Cr (VI), the linear range and limit of detection (LOD) were determined to be 0.05–5 ppm and 0.1 ppb, respectively, based on a three times signal-to-noise ratio. As for Cr (III), the linear range and LOD were found to be 0.05–1 ppm and 0.1 ppb, respectively. After extensive testing, the electrochemical sensor array successfully detected Cr (VI) and Cr (III) in various samples such as tap water, artificial saliva, and artificial sweat. It was also able to monitor the levels of Cr (VI) and Cr (III) during the treatment of chromium-containing wastewater. With the help of a handheld dual-channel electrochemical device, it becomes effortless to simultaneously determine the contents of Cr (VI), Cr (III), and total chromium in different samples (Zhao et al. 2021).

Figure 2. Illustration of preparation of silver-gold bimetallic oxide nanoparticles. Reprinted with permission from (Zhao et al. 2021). Copyright (2021), Elsevier

A novel surface enhanced Raman scattering (SERS) sensor was developed for the first time to identify the increasing water and soil contamination caused by the excessive use of glyphosate, a widely used herbicide in agriculture. This sensor was created by capping reduced graphene oxide (rGO) with silver nanoparticles (AgNPs) on titanium dioxide (TiO2) nanotubes. The sensor performed effectively in detecting methylene blue and glyphosate in water samples, with a limit of detection (LOD) of 10-14 M and 3µg/L, respectively. Furthermore, the sensor demonstrated excellent reproducibility and repeatability, with a relative standard deviation of 2.0% and 4.0% respectively (Butmee et al. 2022). The development of these innovative sensors represents a notable progress in the field of environmental restoration endeavours. The key aspect is in its capability to identify contaminants at extremely low concentrations, given the extensive utilization and the possible environmental consequences. The sensor's exceptional sensitivity and dependability have the potential to enhance the monitoring and control of industrial contaminants, thereby making a significant contribution to the preservation of water and soil resources. These advances not only tackle an urgent environmental issue but also establish a new benchmark for identifying pollutants, opening possibilities for further study and technological advancements in the field of environmental science.

AgNPs as antibacterial agents

Diversified AgNPs were synthesized biogenically from capsid structural proteins of bacteriophage (a naturally occurred bacterial virus) and applied both for the detection of heavy metal ions from the water samples as well as studied for their antibacterial and anti-biofilm properties. The AgNPs were prepared by the bacteriophage mediated reduction of $AgNO_3$. NPs were found to have a particle size of 10 to 30 nm as confirmed by TEM. The developed NPs worked tremendously well and were found to successively inhibit the bacterial biofilm of *S. sciuri* and detect specifically Cd^{2+} ions in the real water samples at a concentration of 100 µM (Abdelsattar et al. 2022). Biogenic recyclable core shell nanoparticles consisting of FeO/AgNPs and FeO/Au NPs were synthesized using pomegranate fruit peel extraction. The formation of the dual types of the nanoparticles was confirmed by different spectral methods. In the UV-visible spectrum, absorbance peaks at 465 nm and 530 nm confirmed the formation of FeO/AgNPs and FeO/AuNPs. Through EMR analysis it was found that in the case of FeO/AgNPs, a 14 nm shell of AgNPs was found to surround the 13 nm Fe core whereas the average size of FeO/AuNPs were found to be less than 100 nm. The *in vitro* antimicrobial and antifungal abilities of the NPs were determined through zone of inhibition and mycelium inhibition method. The results indicated that the NPs possess a good range of antimicrobial properties against all types of microorganisms.

In a recent study by Hidayat et al (2022), synthesis of chitosan stabilized AgNPs immobilized to solid silica gel was developed in an eco-friendly and cost-effective manner (Figure 3 and Figure 4). MeOH was used to create the chi-AgNPs, which were then stabilized using white silica gel beads that had been coated with chitosan, also known as chi-SiG. This process was carried out under the influence of visible light. Using SEM, TEM, UV-visible, FTIR, and other techniques, it was demonstrated that the nanoparticles had formed into a stable, solid, and dispersed form. The nanoparticles (NPs) are extremely stable because of the interaction between several functional groups on the surface of the chitosan and the Ag^+ ion. To combat the multidrug-resistant bacteria *S. aureus*, *E. coli*, and *B. subtilis* that were present in the air, the nanomaterial that had been developed was utilized as an air filter against them. The findings of the bactericidal study showed that the nanoparticles (NPs) have a strong inhibitory effect on the growth of bacterial cells in agar media. Additionally, they demonstrated a higher level of antibacterial activity in the air against the B. subtilis bacterial strain, functioning as a filter for the air. Specifically, the Ag nanoparticles exhibited a mechanistic interaction with the proteins that were present on the bacterial cell wall as well as the phospholipids. This interaction led to the rupture of the cell wall, which in turn inhibited the development of the bacteria (Hidayat et al. 2022).

Figure 3. Characterization of AgNPs immobilized on chi-SIG. Reprinted with permission from (Hidayat et al. 2022). Copyright (2022), Elsevier.

Figure 4. Preparation and antibacterial action of AgNPs. Reprinted with permission from (Hidayat et al. 2022). Copyright (2022), Elsevier

In a recent study, a nanocomposite membrane containing silver nanoparticles was synthesized and utilized for wastewater treatment. At first, the formation of aminated polyether sulfone (NH_2-PES) -silver nanoparticles occurred through the functionalization of $–NH_2$ on polyether sulfone. The AgNPs were immobilized on the NH_2-PES surface, resulting in the formation of the AgNPs-APES. The nanocomposite membrane was characterized by TEM, FTIR, SEM, EDAX, XRD, and other techniques to establish synthesis and immobilization. The findings from the experiments revealed that NPs with diameters ranging from 5 nm to 40 nm were generated and immobilized on the surface of the APES. The nanoparticles have been evaluated for their capacity for inhibiting microorganisms in wastewater. The study revealed that the nanocomposite membrane made with amino functionalized AgNPs-APES exhibited greater antibacterial effectiveness compared to unfunctionalized AgNPs-PES. This could be attributed to the extended lifespan of the membrane, lasting approximately 25 days, because of enhanced and regulated release of Ag^+ ions. The nanoparticles function by impeding the biofouling capability of the pathogens, namely by accumulating AgNPs on the cell wall of the microorganisms, resulting in the rupture of their cell wall and finally preventing bacterial proliferation (Figure 5) (Haider et al. 2016).

Figure 5. Preparation of aminated polyether sulfone decorated by AgNPs.

Recent observations have shown that silver-based porous nanocomposites (AgNCs) have effectively killed bacteria and viruses in drinking water, achieving a reduction of 99% to 100%. Multiple studies have demonstrated that silver nanoparticles have the capability to eliminate around 99.99% of *E. coli* bacteria and MS2 bacteriophage viruses (Bhardwaj et al. 2021).Nanocomposites made of multi-walled carbon nanotubes that were produced with FeO and AgNPs were prepared in order to take into consideration the treatment of wastewater that was contaminated with bacteria. The TEM, SEM, XRD, XRF, and EDAX techniques were utilized to validate the molecular makeup, crystal structure, material, shape, and surface properties of the nanoparticles (NPs). The nanoparticles (NPs) exhibited a noteworthy antibacterial capability in relation to *E. coli*, with a minimum bactericidal concentration of 200 µg/ml. The bacterial growth inhibition time was set at 8 hours (Ali et al. 2017).

Recently, Konduri and colleagues (Konduri et al. 2024) reported on the green manufacturing of silver nanoparticles (AgNPs) from an aqueous extract of the leaves of *Hibiscus tiliaceus* L., as well as its application in the degradation of dyes, antioxidant activities, antibacterial activities, and anticancer activities. X-ray crystallography (XRD) confirmed that the silver nanoparticles were in crystal form, and analysis using Fourier transform infrared (FT-IR) spectroscopy revealed that plant metabolite functional groups had a role in the reduction and stability of silver nanoparticles (AgNPs). The investigations that were conducted using UV–vis spectroscopy, dynamic light scattering (DLS), and zeta potential showed that the AgNPs were produced in colloidal form with an average size of 88.10 nm and were stable (-49 mV). Both the field emission scanning electron microscopy (FE-SEM) and the high-resolution transmission electron microscopy (HR-TEM) techniques were able to confirm that the AgNPs were spherical in shape and had a particle size that ranged from 30 to 35 nanometers. Based on the results of total antioxidant, DPPH, and reducing power experiments, the AgNPs demonstrated the potential to exhibit antioxidant activity. Using the zone of inhibition assay, the biosynthesized silver nanoparticles (AgNPs) demonstrated a broad spectrum of antibacterial activity against Gram-negative and Gram-positive bacteria. There was a significant anticancer activity demonstrated by AgNPs on MCF-7 cells, with an IC50 value of 65.83 µg/mL or higher. Additionally, silver nanoparticles (AgNPs) shown their potential as catalysts when combined with sodium borohydride ($NaBH_4$), a reducing agent, to facilitate the degradation of methylene blue (MB), methylene orange (MO), and methylene green (MG) dyes. The efficiency of catalyst AgNPs in the presence of $NaBH_4$ for 15 minutes was found to be 12.8%, 26.92%, and 47.56% for MO, MB, and MG, respectively. This was confirmed by observing the degradation efficiency of the catalyst AgNPs. According to the findings of the study, green produced silver nanoparticles (AgNPs) have the potential to be extremely relevant in the field of biomedicine as antioxidant, antibacterial, and anticancer agents (Figure 6).

Figure 6. Illustration of a). Mechanism of green synthesis of AgNPs b). Toxicity of AgNPs mediated by ROS response.

AgNPs in dye degradation

Silver nanoparticles (AgNPs) have been thoroughly investigated for their ability to break down synthetic dyes, which pose a significant environmental threat because of their widespread use in many industries and subsequent release into water bodies (Mehta et al. 2021). Recent studies have emphasized the function of biosynthesized AgNPs in removing colors from industrial wastewater (Table 2). An example of a successful process is the use of silver-manganese oxide nanoparticles to degrade Malachite Green dye using photocatalysis. This method has demonstrated high efficiency in breaking down the dye when exposed to sunshine (Pal et al. 2013). The main benefit of utilizing AgNPs for dye degradation lies in their exceptional efficacy in eliminating harmful dyes from water, hence reducing the environmental impact. The eco-friendly green synthesis of AgNPs is conducted using mild conditions, making it a sustainable approach. Moreover, the utilization of AgNPs in the process of dye degradation can result in substantial enhancements in the quality and safety of water (Palani et al. 2023). Despite the benefits, there are certain challenges linked to the utilization of AgNPs. An important drawback is the potential toxicity of nanoparticles, which can provide hazards to human health and the environment if not adequately controlled. Furthermore, the persistent stability and potential buildup of AgNPs in the environment are still subjects of continuing investigation. Ultimately, although silver nanoparticles show potential as a viable method for dye degradation, it is imperative to carefully consider and manage the associated advantages and hazards. Continual research and development are crucial for maximizing their effectiveness in environmental remediation

Table 2. AgNPs for dye removal in wastewater treatment

Future Perspectives

Environmental pollution is increasing globally day by day due to various types of manmade activities which results in multiple kinds of air, water, and soil borne diseases. Nanomaterials made up of AgNPs have found a great deal of environmental applications because of their safe and effective synthesis, tiny particle size with high surface area as well as biocompatibility. At low concentration they are found to be more harmful towards pollutants including dyes, micro-organisms, pathogens, and heavy metal ions, having no adverse effect towards the healthy cells including soil micro-organisms. In this review the authors briefly elaborate the versatile biosynthesis and applications of AgNPs in the form of photocatalyst, electrochemical sensor, fluorogenic sensor etc. towards the detection of hazardous pollutants in the air, water, and soil medium. All the synthesized nanomaterials possess low LOD value with high sensitivity and selectivity towards the detection of pollutants. Due to their biogenic nature, it can also be further recycled and reused.

Conclusions

In conclusion, this study concludes by emphasizing the significance of managing environmental contaminants with silver nanoparticles. Environmental pollution is increasing globally day by day due to various types of manmade activities which results in multiple kinds of air, water, and soil borne diseases. Nanomaterials made up of AgNPs have found a great deal of environmental applications because of their safe and effective synthesis, tiny particle size with high surface area as well as biocompatibility. At low concentration they are found to be more harmful towards the pollutants including dyes, micro-organisms, pathogens, and heavy metal ions, having no adverse effect towards the healthy cells including soil micro-organisms. In this review the authors briefly elaborate the versatile synthesis and applications of AgNPs in the form of photocatalyst, electrochemical sensor, fluorogenic sensor etc. towards the detection of hazardous pollutants in the air, water, and soil medium. All the synthesized nanomaterials possess low LOD value with high sensitivity and selectivity towards the detection of pollutants. Due to their biogenic nature, it can also be further recycled and reused. This review will help the future researchers towards the more economical and efficient innovation of AgNPs carrying nanoprobes which can be efficient to detect multiple groups of pollutants at the same time with low LOD value along with good reproducibility in environment remediation.

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Conflict of Interest

The authors declare no conflict of interest.

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Table 1(on next page)

List of silver-based nano-complexes that have shown potential as detection agents of environmental pollutants in recent years (2016-2023)

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Nanotechnology in Action: Silver Nanoparticles for Improved Environmental Remediation

Table legends

Table 1. List of silver-based nano-complexes that have shown potential as detection agents of environmental pollutants in recent years (2016-2023)

Nano-complex	Molecule detected	Application	Efficiency expressed as limit of detection (LOD)	Reference
Silver nanoparticles synthesized on graphite carbon sheets	Nitrofurazone	A sensor for the detection of nitrofurazone, a possible teratogen and carcinogen, in aqueous systems.	1.2×10^{-8} M	(Zoubir et al. 2022)
Phenylbenzotriazole (PBT) derivative functionalized silver nanoparticles (PBT-AgNPs).	Cr (III)	A sensing probe for detection of Cr (III) during monitoring of water systems, and which has excellent selectivity even in the presence of other interfering metals ions.	0.2 µM	(Qadri et al. 2022)
Curcumin functionalized silver nanoparticles	Paracetamol	To monitor the discharge of pharmaceutical pollutant in water effluent since paracetamol in high dosage can cause organ damage	0.29 µM	(Kumar et al. 2022)
Graphene oxide (rGO)-wrapped dual-layer silver nanoparticles (AgNPs) on titania nanotube (TiO_2 NTs)	Glyphosate	To monitor glyphosate levels using a surface-enhanced Raman scattering (SERS) substrate. Glyphosate is a widely used organophosphate	3 µg/L, which is below the maximum contaminant level of glyphosate in environmental water, as	(Butmee et al. 2022)

arrays		herbicide in agricultural applications that contaminates the environment.	recommended by the U.S. EPA and the European Union.	
AgNPs functionalized with mercaptoundecanoic acid (11-MUA).	Nickel ions	Surface plasmon resonance (SPR) colorimetric sensor of toxic nickel ions especially from industrial water effluent.	Micromolar levels with acceptable selectivity in the presence of Mn^{2+}, Co^{2+}, Cd^{2+}, Cu^{2+}, Zn^{2+}, Fe^{2+}, Hg^{2+}, Pb^{2+}, and Cr^{3+}.	(Rossi et al. 2021)
Gold-silver nanoparticles	Cr (VI) and Cr (III)	An electrochemical sensor array for detection of Cr (VI) and Cr (III) in wastewater treatment processes.	0.1 ppb for both Cr (VI) and Cr (III)	(Zhao et al. 2021)
Silver nanoparticles (AgNP) with different capping agents	Acidic and oxidizing gases and other air pollutants	A colorimetric sensor array for quantitative identification of 11 common pollutants relevant to the protection of cultural heritage objects and for museum environmental monitoring.	Sub-ppb for 1 h exposures	(Li et al. 2020)
Silver nanoparticles synthesized using *Ginkgo biloba*	Chromium (VI)	A fluorescent probe for detection of the toxic hexavalent chromium, especially in water systems.	0.014 µM	(Huang et al. 2020)
Silver-poly (methyl methacrylate) nanoparticles	Hydrogen peroxide	A colorimetric sensor for the detection of hydrogen peroxide, a toxic contaminant that can be found in food, pharmaceuticals, and environmental processes.	10^{-6} M.	(Carbone et al. 2019)
Silver nanoparticles synthesized from *Agaricus bisporus*	Hg (II)	Detection of Hg (II) ions without the use of modifiers or sophisticated instrumentation.	2.1×10^{-6} M.	(Sebastian et al. 2018)

		The Hg (II) ion is very toxic, however due to its stable form, it is highly soluble in water thus leading to severe environmental concerns.		
Silver nanoparticle–reduced graphene oxide–polyaniline (AgNPs–rGO–PANI) nanocomposite	Hydrogen peroxide	A sensor for the detection of hydrogen peroxide, a toxic contaminant that can be found in food, pharmaceuticals, and environmental processes.	50 nM	(Kumar et al. 2018)
Gold nanostar (Au NS) core–silver nanoparticle (Ag NP) satellites	Aflatoxin B1	Surface-enhanced Raman scattering (SERS) sensor for detection of Aflatoxin B1 in the environment, especially in raw food materials, such as grains, corn, feedstu□s and peanuts. Aflatoxins are toxic and recognized as potent carcinogens, mutagens, and teratogens.	0.48 pg/mL	(Li et al. 2016)

Table 2(on next page)

AgNPs for dye removal in wastewater treatment

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Table 2. AgNPs for dye removal in wastewater treatment

No	AgNPs-composites	Type of pollutant	Treatment efficiency	References
1	TiO_2/CNTs/AgNPs/Surfactant nanocomposite	Methylene blue (MB) dye	Degraded in 180 min; 0.5 g^{L-1}, 100%	(Azzam et al. 2019)
2	CNF/PEI/Ag NPs composite	MB	96% after 4 min	(Zhang et al. 2020)
3	CAg-NPs	Congo red (CR), MB, malachite green (MG)	MB: 93.29; MG: 83.73;4-NP: 88.9	(Elbakry et al. 2022)
4	rGO-AgNP (graphene oxide silver nanoparticle hybrid nanocomposite)	Direct blue-14	95.41%	(Choudhary et al. 2021)
5	GO−ZnO−Ag	MB	100%, 40 min	(Naseem et al. 2020)
6	AgNPs/holocellulose nanofibrils (AgNPs/HCNF)	MB	94–98%, catalytic activity with five cycles	(Bandi et al. 2020)
7	AgNPs/ZIF-8 composite	MB and CR	MB: 97.25%; CR: 100%	(Chandra & Nath 2020)
8	AgNPs impregnated sub-micrometer recrystalline jute cellulose (SCJC) particles	CR and MB	100%, 14 min with 0.005 mg/mL	(Rabbi et al. 2020)
9	AgNPs	Reactive green 19A, R blue 59, R red 120, R red 141, and R red 2	180 min, 50; 35% fourth and fifth cycles	(Saratale et al. 2020)
10	Ag@MGO-TA/Fe^{3+} nanocomposite	MB	0.05 mg/mL	(Lai et al. 2022)
11	CH-AgNPs	Orange and blue dyes	97.4 and 100%	(Gola et al. 2021)
12	MMT/Ag nanocomposite	MB	99.90% for 25 ppm; 96.50% for 50 ppm; 89% for 100 ppm and 81.14% for 200 ppm	(Liao et al. 2018)
13	Ag/rGO nanocomposite and Ag/rGO/CA/TFC membranes	MB	98%; 92%	(Vatanpour et al. 2022)
14	AgNPs decorated on nanostructured porous silicon	MB	Degradation rate 8.6/min	(Naveas et al. 2022)
15	$BaTiO_3$/AgNPs	MB and ciprofloxacin	72 and 98%	(Masekela et al. 2022)

2

Figure 1

Multiple techniques of nanoparticle synthesis (Mtambo et al. 2019).

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Nanotechnology in Action: Silver Nanoparticles for Improved Environmental Remediation

Figure legends

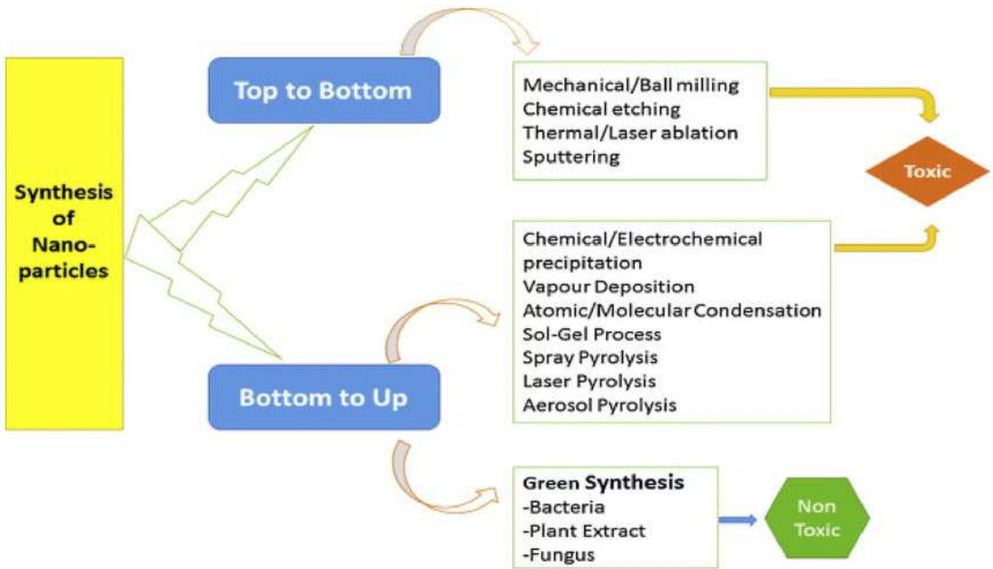

Figure 1. Multiple techniques of nanoparticle synthesis (Mtambo et al. 2019).

Figure 2

Illustration of preparation of silver-gold bimetallic oxide nanoparticles. Reprinted with permission from (Zhao et al. 2021). Copyright (2021), Elsevier

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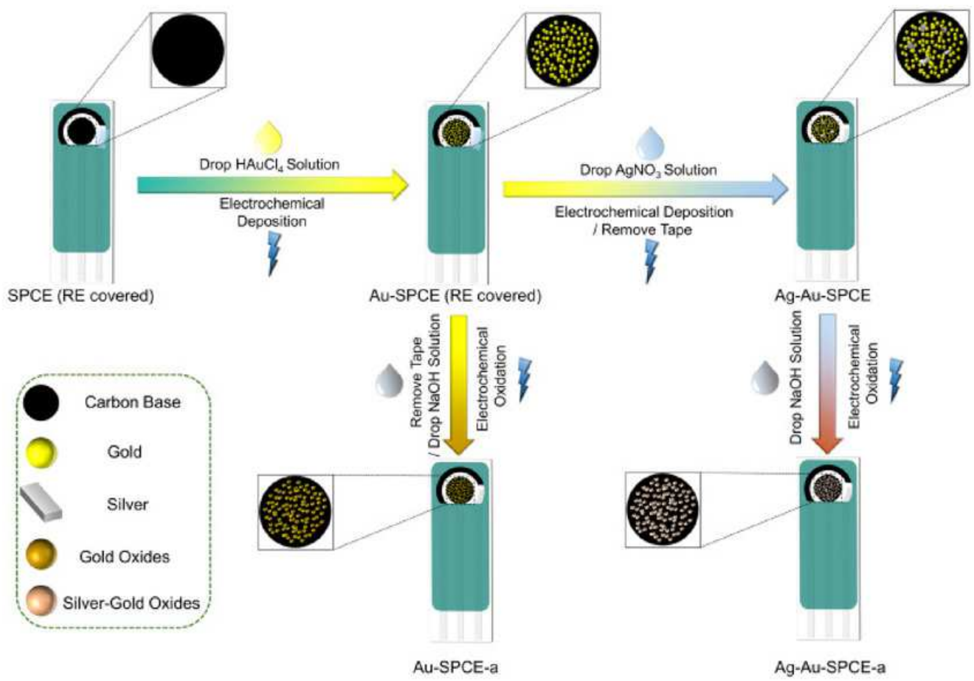

Figure 2. Illustration of preparation of silver-gold bimetallic oxide nanoparticles. Reprinted with permission from (Zhao et al. 2021). Copyright (2021), Elsevier

Figure 3

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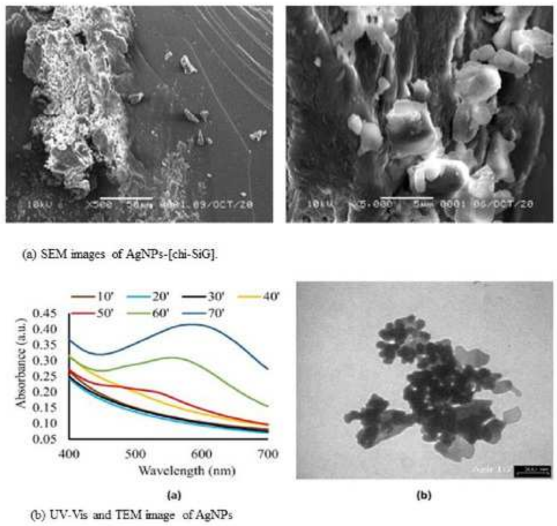

Figure 3. Characterization of AgNPs immobilized on chi-SIG. Reprinted with permission from (Hidayat et al. 2022). Copyright (2022), Elsevier.

Figure 4

Preparation and antibacterial action of AgNPs. Reprinted with permission from (Hidayat et al. 2022). Copyright (2022), Elsevier

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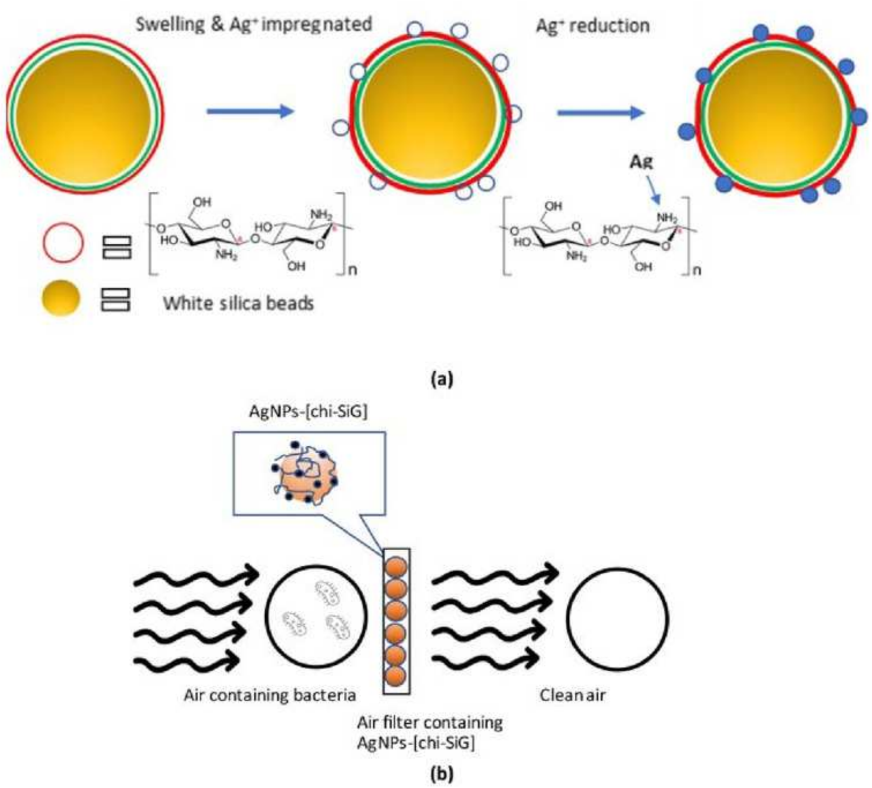

Figure 4. Preparation and antibacterial action of AgNPs. Reprinted with permission from (Hidayat et al. 2022). Copyright (2022), Elsevier

Figure 5

Preparation of aminated polyether sulfone decorated by AgNPs.

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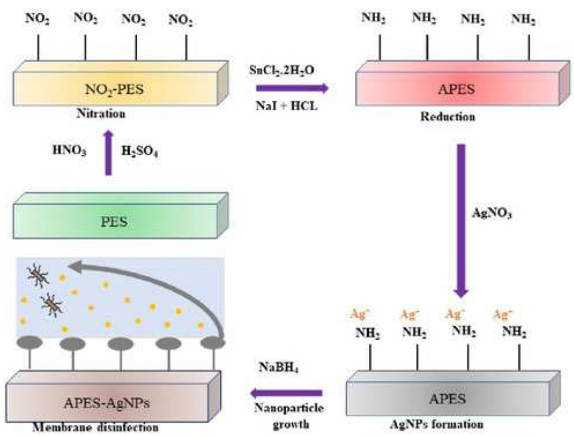

Figure 5. Preparation of aminated polyether sulfone decorated by AgNPs.

Figure 6

Illustration of a). Mechanism of green synthesis of AgNPs b). Toxicity of AgNPs mediated by ROS response.

Illustration of a). Mechanism of green synthesis of AgNPs (b). The toxicity of AgNPs mediated by ROS response.

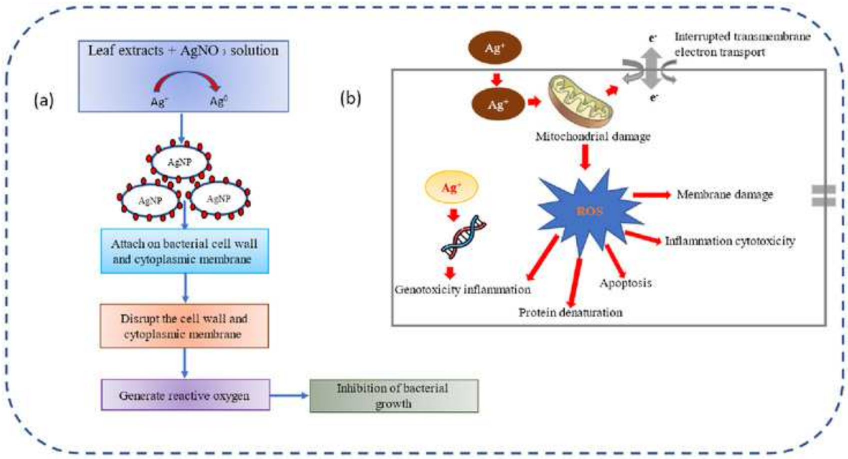

Figure 6. Illustration of a). Mechanism of green synthesis of AgNPs b). Toxicity of AgNPs mediated by ROS response.