Chapter

Silver Nanoparticles for Photocatalysis and Biomedical Applications

William Leonardo da Silva,
Daniel Moro Druzian, Leandro Rodrigues Oviedo,
Pâmela Cristine Ladwig Muraro and Vinícius Rodrigues Oviedo

Abstract

The present chapter aims to overview the application of silver nanoparticles (AgNPs) in photocatalysis and biomedical field. Firstly, the relevance of AgNPs will be addressed. Then, the discussion about the photocatalytic activity of the AgNPs (either in suspension or impregnation), and correlation with your properties and its potential application to organic pollutants degradation under UV and visible/solar radiation will be described. Thus, applications of the AgNPs as antimicrobial agents, such as *Escherichia coli, Schizophyllum commune, Staphylococcus aureus, Pseudomonas aeruginosa, Klebsiella pneumoniae, Haemophilus influenzae, Bacillus subtilis, Bacillus cereus* and *Enterobactor faecalis*, and in the development of biosensors will be discussed. Therefore, the present work will be important to contextualize different scenarios to AgNPs mainly to wastewater treatment and diagnosis/therapeutic applications.

Keywords: nanotechnology, metallic nanoparticles, heterogeneous photocatalysis, antimicrobial properties, biosensors

1. Introduction

Nanotechnology involves the manipulation of materials at nanometric scale (10^{-9} m) and have evolved to novel solutions for water/wastewater treatment as well as biomedical applications [1]. These applications fields are possible due to the unique properties of nanomaterials, such as high surface area, high reactivity and considerable porosity and morphological, electrical, magnetic and/or optical properties, which turn them into useful materials in catalysis, adsorption, sensing and optic-electronic applications [2]. Succinctly, nanomaterials can be divided into 2D, 1D, 0D, according to the number if dimensions the electrons are confined [3]. Metallic nanoparticles are 0D materials, that is, they have the three dimensions within the nanoscale [4]. Among metallic nanoparticles, silver nanoparticles (AgNPs) are largely investigated due to versatility in synthesis, easy processing, fast kinetic reaction rate, high thermal and chemical stability and so forth [5]. Both related to water/wastewater treatment and biomedical applications, AgNPs features allows them to control the interaction with bacteria and, in the case of wastewater

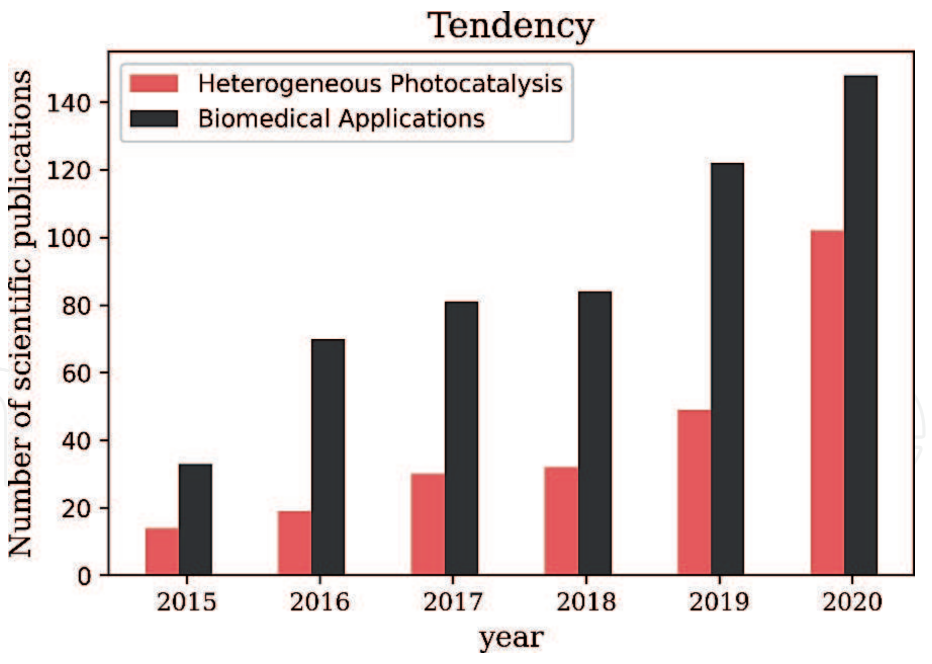

Figure 1.
Number of published papers involving AgNPS in photocatalysis and biomedical applications [7, 8].

treatment, this control can be applied to several pollutants (dyes, hydrocarbons, pesticides, pathogens, and so forth) [6]. Based on that, AgNPs can be applied to photocatalysis and to biomedical applications, such as antimicrobial agents and biosensing [7, 8]. **Figure 1** shows the number of published papers involving AgNPs applied to photocatalysis and biomedical applications.

According to the **Figure 1**, it is possible to notice an increasing tendency of works related to application of AgNPs in the last 5 five years, mainly due to great efficiency of these nanoparticles in sensing applications.

2. Photocatalysis applications with AgNPs

2.1 Water quality deterioration

Mainly due to industrial expansion, climate change, population growth and anthropogenic activities, wastewater quality deterioration has been increased along the years [9]. Wastewater contaminants can be either organic or inorganic [10]. Therefore, the application of an adequate wastewater treatment technology has become a need for minimizing the pollution and the adverse environmental impact as well as for preserving the environment and attending to legal policies of water management [11].

Some of the inorganic ones are well known since ancient times such as chromium, copper, lead, nickel, cadmium, arsenic, mercury and others heavy metals. Theses pollutants pose a serious threat to human health and to environment due to their high toxicity [12]. Meanwhile, organic contaminants, such as benzene, toluene, xylene and natural organic matter (measured by the dissolved or total organic carbon content), are of great concern wastewater management [13]. Usually, the natural organic matter removal from wastewater is challenging and plays a crucial role in defining the treatment technology to be used [14].

In addition, emergent pollutants had been identified in wastewaters all around the world. Most of these contaminants have low biodegradability, high chemical stability, water solubility and are resistant against the conventional wastewater treatment processes [15]. Pharmaceuticals and Personal Care Products (PPCPs) and organic dyes belong to this class of contaminants [16].

Similarly, bacteria commonly pose a threat to humans and to the ecosystem. *Escherichia coli, Enterococcus faecalis*, and *Fusarium solani* are the most contaminants found in wastewater and are of great public concern [17]. Even though they are inactivated by conventional technologies (eg.: chlorination), secondary toxic pollutants are generally found after the treatment, which demonstrate the relatively low-efficiency of the traditional methods of disinfection [18]. Therefore, sophisticated technologies for their inactivation are required, and at same time, it is expected that they do not result in secondary pollutants generation [19].

For these reasons, emergent pollutants (such as pharmaceuticals and dyes), as well as heavy metals, are difficult to remove from wastewater due to either the cost of sophisticated technologies or low efficiency in removing them [20]. In this view, nanotechnology-enable processes seem to be promising to solve the wastewater deterioration quality problem [21]. Therefore, the use of nanoparticles (iron, silver, titanium and zinc oxides) in wastewater applications has been increased due to the unique features of these nanomaterials, requiring treatments with relative low cost and reduction on labor time [22].

Advanced Oxidation Processes (AOPs) have proved to be highly efficient in the degradation of various contaminants like pharmaceuticals, dyes, hydrocarbons, pesticides, and pathogen [23–25]. AOPs are divided into two systems, being [26]: (a) homogeneous, where there are no solid catalysts and the degradation of the organic compound can happen with or without irradiation (direct photolysis), using strong oxidizers (such as hydrogen peroxide, H_2O_2 and ozone, O_3) with or without irradiation, such as photocatalytic ozonolysis and photo-Fenton and, (b) heterogeneous that are characterized by the presence of semiconductor catalysts with or without irradiation, such as heterogeneous photocatalysis and electro-Fenton. Among them, there are processes which are either based on the use of ozone or hydrogen peroxide, decomposition of hydrogen peroxide in acidic media or semiconductors such as titanium dioxide (TiO_2) [27]. The latter one is referred to as a heterogeneous process due to the ease of operation and to sustainable character. Also, it is promising in treating wastewater containing resistant contaminants, once a high percentage of refractory organic contaminants degradation can be achieved [28].

2.2 Heterogeneous photocatalysis

Heterogeneous photocatalysis is an Advanced Oxidation Process (AOPs) useful in the degradation of various contaminants, such as dyes, pharmaceuticals, pesticides, herbicides, hydrocarbons and microorganism inactivation. It can use either UV radiation or visible light to activate a metal-based photocatalyst (generally a semiconductor), promoting oxi-reduction reactions on the catalytic surface with considerable application in wastewater treatment [29]. In this initial step, an electron moves from valence band (VB) to conduction band (CB) of the semiconductor and an electron–hole pair is generated (e^-_{CB} and h^+_{VB}) [30]. Moreover, in this process the water molecules as well as the dissolved oxygen are used as precursors of the reactive oxygen species (ROS) generation [31].

Therefore, ROS (HO• and O_2–•, mainly) tend to react non-selectively with the organic matter and to mineralize it altogether [32]. Thus, heterogeneous photocatalysis is a light-induced catalytic process that reduces or oxidizes organic molecules through redox reactions, which are activated through the electron–hole pairs generated on the surface of the catalyst beyond band gap light irradiation, according to the Eqs. (1)–(8) [33]:

$$Supported\ AgNPs + h\nu \rightarrow e^-_{CB} + h^+_{VB} \quad (1)$$

$$O_2 + e^-_{CB} \rightarrow O_2^- \bullet \quad (2)$$

$$h^+_{VB} + H_2O \rightarrow HO\bullet + H^+ \quad (3)$$

$$e^-_{CB} + h^+_{VB} \rightarrow heat\ loss \quad (4)$$

$$HO\bullet + HO\bullet \rightarrow H_2O_2 \quad (5)$$

$$O_2^- \bullet + H_2O_2 \rightarrow HO\bullet + OH^- + O_2 \quad (6)$$

$$O_2^- \bullet + H^+ \rightarrow HOO\bullet \quad (7)$$

$$HO\bullet + organic\ matter\ O_2 \rightarrow CO_2 + H_2O \quad (8)$$

Thus, the Eq. (1) represents the metal-based photocatalyst (semiconductor) activation yielding to electron–hole pair. Eqs. (2), (3), (6), and (7) are related to ROS generation, which are responsible for organic matter degradation. Eqs. (4) and (5) are undesirable recombination that takes place in the process. Meanwhile, Eq. (4) represents the spontaneous reaction of electron–hole pair recombination, which reduces the photocatalytic degradation efficiency, and Eq. (5) indicates hydrogen peroxide production. Eq. (8) holds for degradation of the organic matter by hydroxyl radicals. Thus, the great advantage of AOPs is that, during the treatment of organic compounds, they are destroyed and not just transferred from one phase to another, as occurs in some conventional homogeneous treatment processes.

Low human toxicity, high stability and relatively low cost are some of the advantages of the heterogeneous photocatalysis process [34]. Moreover, there is a possibility of the complete mineralization of organic pollutants, generating CO_2 and H_2O [35]. In this view, heterogeneous photocatalysis can be applied to degradation of a great number of recalcitrant and non-biodegradable organic pollutants [36, 37].

Moreover, this process can be combined with other processes (either pre-treatment or post-treatment), being performed *in situ*, making use of high oxidative potential agents with fast kinetic reaction and without to need for after-treatment or disposal [38]. In addition, high-quality organoleptic characteristics of water can be achieved, with less energy consumption and low-cost of operation. It is important to mention that the absorbed energy by the semiconductor (and in its photoactivation) is related to the catalyst photocatalytic efficiency, which depends on the competition between the removal of the electron from the semiconductor surface and the recombination of electron–hole pair [39].

2.3 AgNPs-based supported photocatalysts

Individually applied to wastewater treatment, AgNPs proved to be extremely toxic to humans and aquatic life [40]. Moreover, AgNPs can access various organs which most part of the substances cannot [34]. For this reason, AgNPs have been associated to catalytic supports used in heterogeneous photocatalysis [41]. In fact, AgNPs possess considerable photocatalytic activity and when they are impregnated in a less active material, labeled catalytic support, toxicity issues can be fixed [42].

Material	Pollutant	Comment	Reference
Ag@MGO-TA/Fe^{3+}	Methylene Blue (MB)	Excellent stability of the photocatalyst in the aqueous media, high reduction rate (0.054 s^{-1}) for MB, under the dosage of 0.05 mg mL^{-1}. 100% inactivation of *E. coli* using 20 μg.mL^{-1} of photocatalyst	[43]
$nAgFeO_2$	Imidaclopride (IMI)	80% degradation Imidaclopride under UV radiation	[44]
Ag/wood	Methylene Blue and oil separation	The filter can separate selectively the oil from water and dye (about 99%). AgNPs incorporated to filter wood can improve the photocatalytic activity for MB degradation (94.03%)	[45]
Ag@AgBr/Bi_2MoO_6	Reactive Blue-19	Excellent photodegradation of Reactive Blue 19 (98.7%) under visible light after 120 minutes	[46]
C@$CoFe_2O_4$@Ag	Red and Methyl Orange	Fast kinetic of degradation (7 min) for Red Orange and for Methyl Orange (10 min)	[47]
Ag/ZnO/PMMA	Methylene Blue, Paracetamol and Sodium Lauryl Sulfate	90% degradation for the target pollutants after 4 hours under UV radiation	[48]
Ag@CAF and Ag@TiO_2	4-nitrophenol (4-NP), 2-nitrophenol (2-NP), 2-nitroaninile (2-NA), trinitrophenol (TNP), Rhodamine B (RhB) and Methyl Orange (MO)	Nanomaterials exhibited high photocatalytic activity (95%) efficiency was achieved after 10 min	[49]
glass/Ag	Textile wastewater	The coat glass (with AgNPs) yields to about 95% of dye removal after 5 h. In addition, the reusability was studied, targeting microbes found in wastewater. After 2 h, 80% of microbes were inactivated	[50]
Chitosan/Ag	Sodium Fluoresceine	48% dye degradation under anaerobic condition after 2,5 hours. About 51% degradation was achieved under aerobic condition. Chitosan/AgNPs nanocomposite showed antimicrobial activity for gram-positive (*E. coli*) and gram-negative bacteria (*G. bacillus*).	[51]
Fe_3O_4@PPy-MAA/Ag	4-nitrophenol (4-NP), Methylene Blue and Methyl Orange	Excellent catalytic activity towards 4-Nitrophenol, Methyl Orang and Methylene Blue. Good reusability of the nanophotocatalyst	[52]
rGO-Ag	MB and RhB	Degradation of 95% is observed, which is significantly greater that the pristine nanophotocatalyst AgNPs (78%) and rGO (55%)	[53–55]

Table 1.
Paper that apply supported AgNPs as heterogeneous photocatalyst.

It is noteworthy that the main catalytic supports are metallic oxides, since they have favorable characteristics for applicability in heterogeneous photocatalysis, such as photoactivity within a UV–vis radiation range, redox potential of the positive conduction band high enough to promote the mineralization of the organic pollutant, high physical–chemical stability and efficiency in the oxygen reduction reaction. **Table 1** shows some scientific papers found during the 2015–2020, which apply supported AgNPs as heterogeneous photocatalysis.

In addition, the main drawbacks of the metallic nanoparticles, such as nanoparticle agglomeration, can be solved with the application of the Ag-based supported photocatalysts [56]. Thus, impregnation of AgNPs onto ZnO photocatalyst results in better photocatalytic activity, when compared to the use of unsupported ZnO for degradation of Methylene Blue dye. In addition, associations of AgNPs to AuNPs in a core-shell structure leads to a photocatalytic activity comparable with the commonly used TiO_2 photocatalyst. As can be seen, about 80% Methylene Blue degradation can be achieved, when AgNPs supported onto bismuth vanadate ($BiVO_4$) are used [57].

Moreover, with respect to inactivation of bacteria, efficient inactivation degrees for *E. Coli*, *F. Solani*, and *E. faecalis* are reported by means of heterogeneous photocatalysis [58]. Additionally, the efficiency of supported AgNPs for inactivating some pathogens in real wastewaters has been confirmed, resulting in about 80% inactivation [59].

Meanwhile, the utilization of AgNPs as for potentializing the metal-based catalyst and others materials applied to the degradation of organic pollutants or the discoloration of the wastewater is considered an efficient technology, accounting for up to 90% after 180 minutes under UV radiation.

3. Biomedical applications with AgNPs

Silver nanoparticles have been the most investigated, among other metallic nanoparticles for biomedical applications, such as antimicrobial agents and biosensing due their unique physicochemical and biological properties [60]. However, the effective application of AgNPs in the biomedical field is strictly related to their morphology, that is, size and shape [61].

Moreover, one of the main applications of AgNPs, within the biomedical area, consists of acting as an antimicrobial agent, capable of inhibiting the growth of pathogenic microorganisms, being indicated for the treatment of bacterial infections [62]. There are several proposed mechanisms that explain the antimicrobial activity of AgNPs, and all of them lead to applications in wound healing [63], bone tissue [64], and surface coatings [65]. Besides that, optical, electrical and plasmonic properties of AgNPs turn them into interesting nanostructured materials to be used in chemical and biological sensing [66].

Despite being effective against several pathogens and showing promising potential in biosensing, safety concerns are yet a challenge nowadays [67]. In spite of their outstanding properties to biomedical applications, it is known that AgNPs can be toxic to humans depending on the concentration [68] or due to toxic chemicals involved during the synthesis process [69]. To overcome this, nanotechnology has been used together with green chemistry [70], leading to the synthesis of AgNPs by using alternative sources/materials, such as plant extracts, biopolymers and microorganisms (e.g. bacteria and fungi) [71]. Thus, particular interest in evaluating the biocompatibility of green-synthesis derived AgNPs have also been attracting the attention of the scientific community [72]. In the following subsections, both AgNPs applications as antimicrobial agents and as biosensors are discussed.

3.1 Silver nanoparticles as antimicrobial agents

The pathogenic microorganisms are constantly evolving, with a wide genetic diversification, being capable of eliciting several diseases [73]. Although, there are various antimicrobial therapies commercially available, the use of conventional therapies led to the gain of resistance by these pathogenic bacteria [74].

The emerging resistance of bacteria against the conventional antibiotics and metallic ions increased the research in the field of applied nanotechnology, with the AgNPs being among the most potent compounds due to their high specific surface area and number of atoms available to interact with the surroundings, resulting in exhibiting unique properties (electronic, bactericide, magnetic, and optical), since these favorable properties favor the generation of reactive oxygen species (ROS), which they cause changes in the structure of proteins and nucleic acids, and in the permeability of the cell wall, culminating in the lysis of the bacterial cell [75].

The biosynthesis (both intracellular and extracellular) uses microorganisms and show advantages compared to chemical processes: (i) easy strain manipulation, supporting the synthesis process, (ii) easy scaling-up, and (iii) no generation of toxic substances to the environment. However, as the main disadvantages of the biosynthesis using microorganisms is the need to use of the ultrasound to unbind the AgNPs [76, 77].

It is known that the AgNPs have great potential against several gram-negative, gram-positive and antibiotics-resistant bacterial strains [74]. The antimicrobial activity depends on the nanoparticle size and concentration, where low particle sizes with low concentrations can kill bacterial strains and, in the case of green-synthesis derived nanoparticles, this is allied to the advantage of showing lower toxicity to human health and to the environment, leading to a high interest in developing them to combat pathogenic bacteria [78].

The antimicrobial activity of AgNPs against pathogenic bacteria follows two action mechanisms: according to the first one (i), the nanoparticles adhere to the cellular membrane and penetrate the bacteria, promoting alterations on their cellular membrane (due to interactions of silver ions with proteins, sulfur, and phosphorous within the cell, avoiding the electron transport) and, then, resulting in bacterial growth suppression [79]; the other mechanism (ii) involves the silver ions releasing and the production of reactive oxygen species which generates an antimicrobial effect [80].

Moreover, the bacteria are generally unable to develop resistance against AgNPs, which are specially formulated due to their particle size and that allows them to attack a wide range of targets present in the microorganisms, such as proteins, thiol groups and cellular walls [81]. In fact, AgNPs have a huge potential to be used as antimicrobial agents depending on the physicochemical characteristics of these nanoparticles. Therefore, the synergistic effect of these properties, associated with low production cost, good thermal and radiation stability (UV and visible), doing AgNPs effective against pathogenic microorganisms, being promising in biomedical applications to reduce infections. **Table 2** shows the different results of AgNPs against several pathogenic bacteria.

3.2 Silver nanoparticles applied to biosensing

AgNPs have been investigated for chemical and biological sensing. It was already found in literature that the AgNPs present better results than gold nanoparticles (AuNPs) when related to biosensor sensitivity, despite the AuNPs being more investigated for biosensing applications [87]. In addition, AgNPs are plasmonic nanostructures, which means that they can absorb and scatter light [88].

Nanoparticle	Antimicrobial agent	Comments	Reference
Green AgNPs	*Escherichia coli* and *Schizophyllum commune*	Green synthesis using *Eucalyptus camaldulensis* (EC). Moreover, High antimicrobial activity due to the high surface are, which supports better cellular interactions with pathogenic microbes	[82]
Green AgNPs	*Escherichia coli, Staphylococcus aureus, Pseudomonas aeruginosa, Klebsiella pneumoniae* and *Haemophilus influenzae*	Green synthesis using *Artemisia vulgaris* leaves extract (AVLE). In addition, antimicrobial activity with mechanisms involving penetration in the bacteria and silver ions releasing, leading to bacterial growth suppression.	[83]
Green AgNPs	*Bacillus subtilis, Bacillus cereus* and *Staphylococcus aureus*	Green synthesis using *Acorus calamus* rhizome extract. Moreover, nanoparticles exhibited antimicrobial activity when adhering to the bacterial cellular membrane, inhibiting the cellular growth	[84]
Green AgNPs	*Escherichia coli* and *Staphylococcus aureus*	Green synthesis using *Vitex negundo L.* AgNPs showed antimicrobial activity against both gram-positive and gram-negative bacteria	[85]
AgNPs	*Escherichia coli* and *Staphylococcus aureus*	Synthesis by chemical reduction and by using *Petroselinum crispum* plant, and showed antimicrobial activity by penetrating the cellular wall of bacteria	[86]

Table 2.
Results of antimicrobial activity of AgNPs against pathogenic bacteria.

Thus, AgNPs could be used to provide a colorimetric/plasmonic method to detect several biomolecules (including eye-naked verification) due to their light absorption bands - around 400–500 nm [89] - being within the visible range of the electromagnetic spectrum. It is worth pointing out that there are two types of colorimetric/plasmonic biosensors: the aggregation-based and the LSPR-based [90] - some of them are summarized in **Table 3**. Nevertheless, control over morphology during the synthesis of AgNPs is crucial, as anisotropic AgNPs can display various light absorption bands rather than just one [100].

Moreover, Localized Surface Plasmon Resonance (LSPR) phenomenon of AgNPs have turned them into interesting nanomaterials for applications, which involve interaction with light [101]. Thus, when a metallic nanoparticle is irradiated, superficial electrons oscillate collectively, and these generate an electromagnetic field around the nanostructure, called Surface Plasmon Resonance (SPR) [102]. If an external electromagnetic field is applied, in such a way that it is in resonance with the generated electromagnetic field around the metallic nanoparticle, LSPR phenomenon takes place [103]. Thus, the LSPR is possible due to the confinement of the resulting electromagnetic field within the metallic nanoparticle [104, 105].

Moreover, the aggregation-based AgNPs biosensors are considered low-cost, and high-sensitivity biosensing devices, as the aggregation of AgNPs depending on induced changes on the solution medium can be applied to detect DNA molecules, proteins (recognizing) [106]. In this case, aggregation phenomenon and chemical instability of AgNPs is desirable, once it is the working principle of the

Biosensor	Application	Biosensor type	Comment	Reference
AgNPs-based SPR biosensor	MicroRNA (miRNA) detection	LSPR-based	Good sensitivity and selectivity. Excellent reliability. No need for modification procedures to amplify biosensing	[91]
AuNPs/AgNPs biosensor	Cyclin A2	Aggregation-based	Simplicity, high sensitivity, and selectivity. Eye-naked verification allied to quantitative detection. No need for functionalization of the AuNPs/AgNPS. Suitable for peptide-based protein detection. Detection limit: 30 nM.	[92]
Citrate capped silver nanoparticles (Cit-AgNPs)	*Acinetobacter baumannii* detection	Aggregation-based	Accurate and quick detection (about 2 min); low detection limit of quantification (LLOQ) of 1zM.	[93]
Carbon quantum dots (CQDs)/AgNPs nanocomposite	Melamine detection	Aggregation-based	High sensitivity, simple method of detection, and eye-naked verification allied to quantitative detection. Detection limit: 65.3 $pmol.L^{-1}$.	[94]
Glutathione-coated AgNPs	Vitamin B1 (thiamine) detection	LSPR-based	Provides both qualitative (colorimetric) and quantitative sensing. High sensitivity and selectivity; low-cost, quick, and simple detection. Worked well with real samples, such as blood and urine.	[95]
Grown-AgNPs on AuNS	Alkaline phosphatase (ALP) detection	LSPR-based	Provides both qualitative (colorimetric) and quantitative sensing. Could be extended to a general device for immunosensors/ aptasensors designs.	[96]
SiO_x/AgNPs/ Graphene	DNA hybridization detection	LSPR-based	Other applications may involve enzyme detection, medical diagnostics, food safety, and environmental monitoring. Sensitivity improvement of 304.60% compared to pure AgNPs.	[97]
Ag@AgCl nanotubes loaded onto reduced graphene oxide (RGO)	Ochratoxin A (OTA) detection	LSPR-based	Good accuracy, high sensitivity, and good reproducibility. High stability and photocurrent response under visible light irradiation. Range of detection: 0.05 to 300 n mol L^{-1}, limit of detection (LOD): 0.01 n mol L^{-1} (4.0 pg. mL^{-1}).	[98]
AgNPs-based aptasensor	Adenosine detection	LSPR-based	High sensitivity and selectivity. Simple and specific design, low-cost, and quick detection. Linear range of detection: 200 n mol L^{-1} to 200 μ mol L^{-1}, detection limit: 48 n mol L^{-1}.	[99]

Table 3.
AgNPs-based biosensors for biomedical applications.

biosensor [107]. LSPR-based ones are established on changes in the occurring refractive index now that photons are directed to the nanoparticles, leading them to oscillation [108], being used in biomolecules detection [109]. It is also important to mention that AgNPs are normally functionalized before applying them as biosensors to overcome chemical stability and toxicity aspects [110]. Therefore, coating AgNPs with organic or inorganic materials are the common approaches. Furthermore, polymeric coatings are also used to functionalize AgNPs by using either synthetic polymers, such as (poly)-ethylene glycol (PEG) [111], (poly)-vinyl alcohol (PVA) [112] and (Poly)-vinylpyrrolidone (PVP) [113], or natural polymers such as starch [114], sodium alginate [115] and chitosan [116]. Functionalization with polymeric blends that uses both synthetic and natural polymers is also an interesting approach (e.g. PVA/Chitosan-coated AgNPs [117]). The inorganic coating involves the functionalization of AgNPs with silicon dioxide [118], while organic coating involves citrates mainly [119]. Furthermore, there are plenty of electrochemical-based AgNPs biosensors [120, 121], however, they will not be covered here as the focus is on the plasmonic ones. Another possible application of AgNPs is the surface enhanced Raman Spectroscopy (SERS), which involves the adsorption of molecules on the AgNPs to achieve a high-quality spectroscopy technique. The applications of SERS focus on disease diagnosis caused by microbial infections or cancer [122].

Therefore, AgNPs-based biosensors are good alternatives against conventional sensing devices, as nanostructured biosensors show greater sensibility, reliability, wide limits of detection, precision, speed and provides eye-naked colorimetric assays together with quantitative analysis [123], among other unique characteristics that are shown in the papers summarized in **Table 3.**

4. Conclusion

Regarding the use AgNPs in heterogeneous photocatalysis, it can be proved highly efficient in the degradation a large amount of organic pollutants and inactivation of bacteria and pathogens, under either UV radiation or visible light. Moreover, when supported AgNPs-based nanophotocatalysts are used in wastewater not only the photocatalytic activity is enhanced, but also some operational problems (nanoparticles agglomeration) can be fixed. With respect to the use of AgNPs as antimicrobial agents, it is a current alternative against common pathogens and multi-resistant bacteria due to the toxicity to microorganisms compared to antibiotics and conventional approaches. In addition, AgNPs-based biosensors are resulting in high sensitivity and selectivity aligned to wide detection limits, which turns them suitable for clinical practice. It is worth to point out that the green synthesis of AgNPs is increasing along the years, and when combined with photocatalytic and biomedical applications, contributes to sustainable development and biocompatibility aspects.

Acknowledgements

This work received financial support from the Foundation for Research of the State of Rio Grande do Sul (FAPERGS – Project 19/2551-0001362-0), so all thanks.

Conflict of interest

The authors declare no competing interests.

Author details

William Leonardo da Silva*, Daniel Moro Druzian, Leandro Rodrigues Oviedo, Pâmela Cristine Ladwig Muraro and Vinícius Rodrigues Oviedo
Nanoscience Graduate Program – Universidade Franciscana, Santa Maria - RS, Brazil

*Address all correspondence to: w.silva@ufn.edu.br

References

[1] Wen M, Li G, Liu H, Chen J, An T, Yamashita H. Metal–organic framework-based nanomaterials for adsorption and photocatalytic degradation of gaseous pollutants: recent progress and challenges. Environmental Science: Nano. 2019;6(4):1006-1025. DOI:10.1039/c8en01167b

[2] Das R, Ali ME, Hamid SBA, Ramakrishna S, Chowdhury ZZ. Carbon nanotube membranes for water purification: A bright future in water desalination. Desalination. 2014;336:97-109. DOI:10.1016/j.desal.2013.12.026

[3] Zhang B, Sun JY, Ruan MY, Gao PX. Tailoring two-dimensional nanomaterials by structural engineering for chemical and biological sensing. Sensors and Actuators Reports. 2020;2(1):1-12. DOI:10.1016/j.snr.2020.100024

[4] Varshney S, Kumar M, Gowda A, Kumar S. Soft discotic matrix with 0-D silver nanoparticles: Impact on molecular ordering and conductivity. Journal of Molecular Liquids. 2017;238:290-295. DOI:10.1016/j.molliq.2017.05.008

[5] Nagaraju G, Udayabhanu, Shivaraj, Prashanth SA, Shastri M, Yathish KV, Anupama, C; Rangappa, D, Nagaraju, G. Electro-chemical heavy metal detection, photocatalytic, photoluminescence, biodiesel production and antibacterial activities of Ag–ZnO nanomaterial. Materials Research Bulletin. 2017;94:54-63. DOI:10.1016/j.materresbull.2017.05.043

[6] Qu X, Brame J, Li Q, Alvarez PJJ. Nanotechnology for a Safe and Sustainable Water Supply: Enabling Integrated Water Treatment and Reuse. Accounts of Chemical Research. 2012;46(3):834-843. DOI:10.1021/ar300029v

[7] Kamarudin NS, Jusoh R, Setiabudi HD, Sukor NF, Shariffuddin JH. Potential nanomaterials application in wastewater treatment: Physical, chemical and biological approaches. Materials Today: Proceedings. 2020:1-13. DOI:10.1016/j.matpr.2020.10.221

[8] Shen T, Wang J, Xia Z, Dai X, Li B, Feng Y. Ultraviolet sensing characteristics of Ag-doped ZnO micro-nano fiber. Sensors and Actuators A: Physical. 2020;307:1-8. DOI:10.1016/j.sna.2020.111989

[9] Zhang S, Liu Y, Gu P, Ma R, Wen T, Zhao G, Li L, Ai Y, Hu C, Wang X. Enhanced photodegradation of toxic organic pollutants using dual-oxygen-doped porous g-C3N4: Mechanism exploration from both experimental and DFT studies. Applied Catalysis B: Environmental. 2019;248:1-10. DOI:10.1016/j.apcatb.2019.02.008

[10] Tahir MB, Nawaz T, Nabi G, Sagir M, Khan MI, Malik N. Role of nanophotocatalysts for the treatment of hazardous organic and inorganic pollutants in wastewater. International Journal of Environmental Analytical Chemistry. 2020:1-25. DOI:10.1080/03067319.2020.1723570

[11] Hernández-Chover V, Castellet-Viciano L, Hernández-Sancho F. Preventive maintenance versus cost of repairs in asset management: An efficiency analysis in wastewater treatment plants. Process Safety and Environmental Protection. 2020;141:215-221. DOI:10.1016/j.psep.2020.04.035

[12] Ali I. New Generation Adsorbents for Water Treatment. Chemical Reviews. 2012;112(10):5073-5091. DOI:10.1021/cr300133d

[13] Mello JMM, Brandao HL, Valério A, de Souza AAU, de Oliveira D,

da Silva A, et al. Biodegradation of BTEX compounds from petrochemical wastewater: Kinetic and toxicity. Journal of Water Process Engineering. 2019;32:1-7. DOI:10.1016/j.jwpe.2019.100914

[14] Matilainen A, Gjessing ET, Lahtinen T, Hed L, Bhatnagar A, Sillanpaää M. An overview of the methods used in the characterization of natural organic matter (NOM) in relation to drinking water treatment. Chemosphere. 2011;83(11):1431-1442. DOI:10.1016/j.chemosphere.2011.01.018

[15] Bernabeu A, Vercher RF, Santos-Juanes L, Simon PJ, Lardíın C, Martíınez MA, Vicente JA, González R, Llosá C, Amant AM. Solar photocatalysis as a tertiary treatment to remove emerging pollutants from wastewater treatment plant effluents. Catalysis Today. 2011;161(1):235-240. DOI:10.1016/j.cattod.2010.09.025

[16] Mohapatra DP, Brar SK, Tyagi RD, Picard P, Surampalli RY. Analysis and advanced oxidation treatment of a persistent pharmaceutical compound in wastewater and wastewater sludge-carbamazepine. Science of the Total Environment. 2014;470-471:58-75. DOI:10.1016/j.scitotenv.2013.09.034

[17] Yan Y, Zhou X, Yu P, Li Z, Zheng T. Characteristics, mechanisms and bacteria behavior of photocatalysis with a solid Z-scheme Ag/AgBr/g-C_3N_4 nanosheet in water disinfection. Applied Catalysis A: General. 2020;590:1-27. DOI:10.1016/j.apcata.2019.117282

[18] Meng Y, Wang Y, Han Q, Xue N, Sun Y, Gao B, Li Q. Trihalomethane (THM) formation from synergic disinfection of biologically treated municipal wastewater: Effect of ultraviolet (UV) irradiation and titanium dioxide photocatalysis on dissolve organic matter fractions. Chemical Engineering Journal. 2016;303:252-260. DOI:10.1016/j.cej.2016.05.141

[19] Madhura L, Singh S, Kanchi S, Sabela M, Bisetty K, Inamuddin. Nanotechnology-based water quality management for wastewater treatment. Environmental Chemistry Letters. 2018;17(1):65-121. DOI:10.1007/s10311-018-0778-8

[20] Shah AI, Dar MUD, Bhat RA, Singh JP, Singh K, Bhat SA. Perspectives and challenges of wastewater treatment technologies to combat contaminants of emerging concerns. Ecological Engineering. 2020;152:105882. DOI:10.1016/j.ecoleng.2020.105882

[21] Theron J, Walker JA, Cloete TE. Nanotechnology and Water Treatment: Applications and Emerging Opportunities. Critical Reviews in Microbiology. 2008;34(1):43-69. DOI:10.1080/10408410701710442

[22] Kanchi S. Nanotechnology for Water Treatment. Journal of Environmental Analytical Chemistry. 2014;01(02):1-3. DOI:10.4172/JREAC.1000e102

[23] Kosera VS, Cruz TM, Chaves ES, Tiburtius ERL. Triclosan degradation by heterogeneous photocatalysis using ZnO immobilized in biopolymer as catalyst. Journal of Photochemistry and Photobiology A: Chemistry. 2017;344:184-191. DOI:10.1016/j.jphotochem.2017.05.014

[24] Nobre FX, Mariano FAF, Santos FEP, Rocco MLM, Manzato L, de Matos JME, Couceiro P, Brito W. Heterogeneous photocatalysis of Tordon 2, 4-D herbicide using the phase mixture of TiO_2. Journal of Environmental Chemical Engineering. 2019;7(6):1-46. DOI:10.1016/j.jece.2019.103501

[25] Castaneda-Juáarez M, Martínez-Miranda V, Almazan-Sánchez PT, Linares-Hernández I, Santoyo-Tepole F,

Vázquez-Mejía G. Synthesis of TiO_2 catalysts doped with Cu, Fe, and Fe/Cu supported on clinoptilolite zeolite by an electrochemical-thermal method for the degradation of diclofenac by heterogeneous photocatalysis. Journal of Photochemistry and Photobiology A: Chemistry. 2019;380:1-10. DOI:10.1016/j.jphotochem.2019.04.045

[26] Nie G, Xiao L. New insight into wastewater treatment by activation of sulfite with photosensitive organic dyes under visible light irradiation. Chemical Engineering Journal. 2020;389:1-9. DOI:10.1016/j.cej.2019.123446

[27] Pandoli O, Rosso TD, Santos VM, de Siqueira Rezende R, Marinkovic BA. Prototyping of photocatalytic microreactor and testing of photodegradation of organic dye. Química Nova. 2015;38(6):859-863. DOI:10.5935/0100-4042.20150079

[28] Pereira VJ, Fernandes D, Carvalho G, Benoliel MJ, Romão MVS, Crespo MTB. Assessment of the presence and dynamics of fungi in drinking water sources using cultural and molecular methods. Water Research. 2010;44(17):4850-4859. DOI:10.1016/j.watres.2010.07.018

[29] Díez AM, Moreira FC, Marinho BA, Espíındola JCA, Paulista LO, Sanroman MA, Pazos M, Boaventura RAR, Vilar VJP. A step forward in heterogeneous photocatalysis: Process intensification by using a static mixer as catalyst support. Chemical Engineering Journal. 2018;343:597-606. DOI:10.1016/j.cej.2018.03.041

[30] Gonçalves NPF, Paganini MC, Armillotta P, Cerrato E, Calza P. The effect of cobalt doping on the efficiency of semiconductor oxides in the photocatalytic water remediation. Journal of Environmental Chemical Engineering. 2019;7(6):1-16. DOI:10.1016/j.jece.2019.103475

[31] Cambrussi ANCO, de Sena Neto LR, da Silva Filho EC, Osajima JAF, Ribeiro AB. Heterogeneous photocatalysis using TiO_2 in suspension applied to antioxidant activity assays. Materials Today: Proceedings. 2019;14:648-655. DOI:10.1016/j.matpr.2019.02.002

[32] Zerjav G, Albreht A, Vovk I, Pintar A. Revisiting terephthalic acid and coumarin as probes for photoluminescent determination of hydroxyl radical formation rate in heterogeneous photocatalysis. Applied Catalysis A: General. 2020;598:1-7. DOI:10.1016/j.apcata.2020.117566

[33] Gaya UI, Abdullah AH. Heterogeneousphotocatalyticdegradation of organic contaminants over titanium dioxide: A review of fundamentals, progress and problems. Journal of Photochemistry and Photobiology C: Photochemistry Reviews. 2008;9(1):1-12. DOI:10.1016/j.jphotochemrev.2007.12.003

[34] Kunduru KR, Nazarkovsky M, Farah S, Pawar RP, Basu A, Domb AJ. Nanotechnology for water purification: applications of nanotechnology methods in wastewater treatment. In: Grumezescu AM, editor. Water Purification. Amsterdan: Elsevier; 2017. 33-74. DOI:https://doi.org/10.1016/B978-0-12-804300- 4.00002-2

[35] Patel SG, Yadav NR, Patel SK. Evaluation of Degradation Characteristics of Reactive Dyes by UV/Fenton, UV/Fenton/Activated Charcoal, and UV/Fenton/TiO_2 Processes: A Comparative Study. Separation Science and Technology. 2013;48(12):1788-1800. DOI:10.1080/01496395.2012.756035

[36] Da Silva WL, Lansarin MA, Stedlie FC, Dos Santos JH. The potential of chemical industrial and academic wastes as a source of supported photocatalysts. Journal of Molecular

Catalysis. A, Chemical. 2014; 393: 125-133. DOI: 10.1016/j.molcata.2014.05.040

[37] Apostila do Curso da Escola Piloto: Técnicas de Controle Ambiental em efluentes líquidos – Processos Oxidativos Avançados. Rio de Janeiro: Universidade Federal do Rio de Janeiro; 1993

[38] Gehrke I, Geiser A, Somborn-Schulz A. Innovations in nanotechnology for water treatment. Nanotechnology, Science and Applications. 2015;8:1-17. DOI:10.2147/NSA.S43773

[39] Lazar M, Varghese S, Nair S. Photocatalytic Water Treatment by Titanium Dioxide: Recent Updates. Catalysts. 2012;2(4):572-601. DOI: https://doi.org/10.3390/catal2040572

[40] Aani SA, Gomez V, Wright CJ, Hilal N. Fabrication of antibacterial mixed matrix nanocomposite membranes using hybrid nanostructure of silver coated multi-walled carbon nanotubes. Chemical Engineering Journal. 2017;326:721-736. DOI: https://doi.org/10.1016/j.cej.2017.06.029

[41] Zabihi-Mobarakeh H, Nezamzadeh-Ejhieh A. Application of supported TiO_2 onto Iranian clinoptilolite nanoparticles in the photodegradation of mixture of aniline and 2, 4-dinitroaniline aqueous solution. Journal of Industrial and Engineering Chemistry. 2015;26:315-321. DOI:10.1016/j.jiec.2014.12.003

[42] Zou Y, Huang H, Li S, Wang J, Zhang Y. Synthesis of supported Ag/AgCl composite materials and their photocatalytic activity. Journal of Photochemistry and Photobiology A: Chemistry. 2019;376:43-53. DOI:10.1016/j.jphotochem.2019.03.00

[43] Yang W, Hu W, Zhang J, Wang W, Cai R, Pan M, Huang C, Chen X, Yan B, Zeng H. Tannic acid/Fe^{3+} functionalized magnetic graphene oxide nanocomposite with high loading of silver nanoparticles as ultra-efficient catalyst and disinfectant for wastewater treatment. Chemical Engineering Journal. 2021;405:1-10. DOI:10.1016/j.cej.2020.126629

[44] Kan Q, Lu K, Dong S, Shen D, Huang Q, Tong Y, Wu W, Gao S, Mao L. Transformation and removal of imidacloprid mediated by silver ferrite nanoparticle facilitated peroxymonosulfate activation in water: Reaction rates, products, and pathways. Environmental Pollution. 2020;267:1-13. DOI:10.1016/j.envpol.2020.115438

[45] Cheng Z, Guan H, Meng J, Wang X. Dual-Functional Porous Wood Filter for Simultaneous Oil/Water Separation and Organic Pollutant Removal. ACS Omega. 2020;5(23):14096-14103. DOI:10.1021/acsomega.0c01606

[46] Yang R, Zhao Q, Liu B. Two-step method to prepare the direct Z-scheme heterojunction hierarchical flowerlike $Ag@AgBr/Bi_2MoO_6$ microsphere photocatalysts for wastewater treatment under visible light. Journal of Materials Science: Materials in Electronics. 2020;31(7):5054-5067. DOI:10.1007/s10854-020-03040-3

[47] Bodaghi Z, Pakpour F, Ghanbari D. $Carbon@CoFe_2O_4@Ag$ and hollow $CoFe_2O_4@Ag$ nanocomposite: green synthesis of a photocatalyst and magnetic adsorbent for antibiotic removal from aqueous solutions. Journal of Materials Science: Materials in Electronics. 2020. DOI:10.1007/s10854-020-04439-8

[48] Mauro AD, Farrugia C, Abela S, Refalo P, Grech M, Falqui L, Nicotra G, Sfuncia G, Mio A, Buccheri MA, Rappazzo G, Brundo MV, Scalisi EM, Pecoraro RP, Iaria C, Privitera V, Impellizzeri G. Ag/ZnO/PMMA Nanocomposites for Efficient Water Reuse. ACS Applied Bio

Materials. 2020;3(7):4417-4426. DOI:10.1021/acsabm.0c00409

[49] Albukhari SM, Ismail M, Akhtar K, Danish EY. Catalytic reduction of nitrophenols and dyes using silver nanoparticles @ cellulose polymer paper for the resolution of wastewater treatment challenges. Colloids and Surfaces A: Physicochemical and Engineering Aspects. 2019;577:548-561. DOI:10.1016/j.colsurfa.2019.05.058

[50] Mazumder JA, Perwez M, Noori R, Sardar M. Development of sustainable and reusable silver nanoparticlecoated glass for the treatment of contaminated water. Environmental Science and Pollution Research. 2019;26(22):23070-23081. DOI:10.1007/s11356-019-05647-4

[51] Al-Sherbini ASA, Ghannam HEA, El-Ghanam GMA, El-Ella AA, Youssef AM. Utilization of chitosan/Ag bionanocomposites as eco-friendly photocatalytic reactor for Bactericidal effect and heavy metals removal. Heliyon. 2019;5(6):e01980. DOI:10.1016/j.heliyon.2019.e01980

[52] Das R, Sypu VS, Paumo HK, Bhaumik M, Maharaj V, Maity A. Silver decorated magnetic nanocomposite (Fe_3O_4@PPy-MAA/Ag) as highly active catalyst towards reduction of 4-nitrophenol and toxic organic dyes. Applied Catalysis B: Environmental. 2019;244:546-558. DOI:10.1016/j.apcatb.2018.11.073

[53] Pratheesya T, Harish S, M N, Sohila S, Ramesh R. Enhanced antibacterial and photocatalytic activities of silver nanoparticles anchored reduced graphene oxide nanostructure. Materials Research Express. 2019;6(7):1-25. DOI:10.1088/2053-1591/ab1567

[54] Rasool K, Lee DS. Inhibitory Effects of silver nanoparticles on removal of organic pollutants and sulfate in an anaerobic biological wastewater treatment process. Journal of Nanoscience and Nanotechnology. 2016;16(5):4456-4463. DOI:10.1166/jnn.2016.10984

[55] Casa M, Sarno M, Cirillo C, Ciambelli P. Reduced graphene oxide-based silver nanoparticle-containing natural hydrogel as highly efficient catalysts for nitrile wastewater treatment. Chemical Engineering Transactions. 2016;47:307-312. DOI:10.3303/CET1647052

[56] Chen X, Cen C, Tang Z, Zeng W, Chen D, Fang P, Chen Z. The key role of pH value in the synthesis of titanate nanotubes-loaded manganese oxides as a superior catalyst for the selective catalytic reduction of NO with NH_3. Journal of Nanomaterials. 2013;2013:1-7. DOI:10.1155/2013/871528

[57] Mahardika T, Putri NA, Putri AE, Fauzia V, Roza L, Sugihartono I, Herbani Y. Rapid and low temperature synthesis of Ag nanoparticles on the ZnO nanorods for photocatalytic activity improvement. Results in Physics. 2019;13:1-9. DOI:10.1016/j.rinp.2019.102209

[58] Booshehri AY, Goh SCK, Hong J, Jiang R, Xu R. Effect of depositing silver nanoparticles on BiVO4in enhancing visible light photocatalytic inactivation of bacteria in water. J Mater Chem A. 2014;2(17):6209-6217. DOI:10.1039/c3ta15392d

[59] Radhu S. Photocatalytic degradation of textile dye molecules by Ag@Au core–shell nanoparticles. Materials Today: Proceedings. 2020;25:285-288. DOI:10.1016/j.matpr.2020.01.413

[60] Burdusel AC, Gherasim O, Grumezescu AM, Mogoanta L, Ficai A, Andronescu E. Biomedical Applications of Silver Nanoparticles: An Up-to-Date Overview. Nanomaterials.

2018;8(9):681. DOI:10.3390/nano8090681

[61] Nedelcu IA, Ficai A, Sonmez M, Ficai D, Oprea O, Andronescu E. Silver Based Materials for Biomedical Applications. Current Organic Chemistry. 2014;18(2):173-184. DOI:10.2174/13852728113176660141

[62] Ivask A, Juganson K, Bondarenko O, Mortimer M, Aruoja V, Kasemets K, et al. Mechanisms of toxic action of Ag, ZnO and CuO nanoparticles to selected ecotoxicological test organisms and mammalian cells in vitro: A comparative review. Nanotoxicology. 2013;8(sup1):57-71. DOI:10.3109/17435390.2013.855831

[63] Kumar SSD, Rajendran NK, Houreld NN, Abrahamse H. Recent advances on silver nanoparticle and biopolymer-based biomaterials for wound healing applications. International Journal of Biological Macromolecules. 2018;115:165-175. DOI:10.1016/j.ijbiomac.2018.04.003

[64] Brennan SA, Fhoghlú CN, Devitt BM, O'Mahony FJ, Brabazon D, Walsh A. Silver nanoparticles and their orthopaedic applications. The Bone & Joint Journal. 2015;97-B(5):582-589. DOI:10.1302/0301- 620x.97b5.33336

[65] Marassi V, Cristo LD, Smith SGJ, Ortelli S, Blosi M, Costa AL, Reschiglian P, Volkov Y, Prina-Melo A. Silver nanoparticles as a medical device in healthcare settings: a five-step approach for candidate screening of coating agents. Royal Society Open Science. 2018;5(1):1-21. DOI:10.1098/rsos.171113

[66] Pala R, Zeng Y, Pattnaik S, Busi S, Alomari N, Nauli SM, Liu G. Functionalized silver nanoparticles for sensing, molecular imaging and therapeutic applications. Current Nanomedicine. 2019;8(3):234-250. DOI:10.2174/2468187308666180508144919

[67] Mao BH, Chen ZY, Wang YJ, Yan SJ. Silver nanoparticles have lethal and sublethal adverse effects on development and longevity by inducing ROS-mediated stress responses. Scientific Reports. 2018;8(1). DOI:10.1038/s41598-018-20728-z

[68] Pauksch L, Hartmann S, Rohnke M, Szalay G, Alt V, Schnettler R, Lips KS. Biocompatibility of silver nanoparticles and silver ions in primary human mesenchymal stem cells and osteoblasts. Acta Biomaterialia. 2014;10(1):439-449. DOI:10.1016/j.actbio.2013.09.037

[69] Ibrahim EH, Kilany M, Ghramh HA, Khan KA, Ul Islam S. Cellular proliferation/cytotoxicity and antimicrobial potentials of green synthesized silver nanoparticles (AgNPs) using Juniperus procera. Saudi Journal of Biological Sciences. 2019;26(7):1689-1694. DOI:10.1016/j.sjbs.2018.08.014

[70] Elia P, Zach R, Hazan S, Kolusheva S, Porat Z, Zeiri Y. Green synthesis of gold nanoparticles using plant extracts as reducing agents. International journal of nanomedicine. 2014;9:4007-4021. DOI:10.2147/IJN.S57343

[71] Tarannum N, Divya D, Gautam YK. Facile green synthesis and applications of silver nanoparticles: a state-of-the-art review. RSC Advances. 2019;9(60):34926-34948. DOI:10.1039/c9ra04164h

[72] Srikar SK, Giri DD, Pal DB, Mishra PK, Upadhyay SN. Green synthesis of silver nanoparticles: A review. Green and Sustainable Chemistry. 2016;06(01):34-56. DOI:10.4236/gsc.2016.61004

[73] Kyriacou SV, Brownlow WJ, Xu XHN. Using nanoparticle optics assay for direct observation of the function of antimicrobial agents in single live bacterial cells. Biochemistry.

2004;43(1):140-147. DOI:10.1021/bi0351110

[74] Kim JS, Kuk E, Yu KN, Kim JH, Park SJ, Lee HJ, Kim SH, Park YK, Park, YH, Hwang C, Kim Y, Lee Y, Jeong H, Cho M. Antimicrobial effects of silver nanoparticles. Nanomedicine: Nanotechnology. Biology and Medicine. 2007;3(1):95-101. DOI:10.1016/j.nano.2006.12.001

[75] Sahar MO. Some Nanoparticles effects on proteus sp. and klebsiella sp. isolated from water. American Journal of Infectious Diseases and Microbiology. 2014;2(1):4-10. DOI:10.12691/ajidm-2-1-2

[76] Jain D, Daima H, Kachhwala S, Kothari S. Synthesis of plant-mediated silver nanoparticles using papaya fruit extract and evaluation of their Anti Microbial Activities. Digest Journal of Nanomaterials and Biostructures. 2009;4:557-563

[77] Kvítek L, Panácek A, Soukupová J, Kolár M, Vecerovpa R, Prucek R, Holecová M, Zbořil R. Effect of surfactants and polymers on stability and antibacterial activity of silver nanoparticles (NPs). The Journal of Physical Chemistry C. 2008;112(15):5825-5834. DOI:10.1021/jp711616v

[78] Khan SU, Anjum SI, Ansari MJ, Khan MHU, Kamal S, Rahman K, Shoaib M, Man S, Khan AJ, Khan SU, Khan D. Antimicrobial potentials of medicinal plant's extract and their derived silver nanoparticles: A focus on honey bee pathogen. Saudi Journal of Biological Sciences. 2019;26(7):1815-1834. DOI:10.1016/j.sjbs.2018.02.010

[79] Sanjivkumar M, Vaishnavi R, Neelakannan M, Kannan D, Silambarasan T, Immanuel G. Investigation on characterization and biomedical properties of silver nanoparticles synthesized by an actinobacterium Streptomyces olivaceus (MSU3). Biocatalysis and Agricultural Biotechnology. 2019;17:151-159. DOI:10.1016/j.bcab.2018.11.014

[80] Scheringer M, MacLeod M, Behra R, Sigg L, Hungerbühler K. Environmental risks associated with nanoparticulate silver used as biocide. Household Pers Care Today. 2010;1:34-37

[81] MubarakAli D, Thajuddin N, Jeganathan K, Gunasekaran M. Plant extract mediated synthesis of silver and gold nanoparticles and its antibacterial activity against clinically isolated pathogens. Colloids and Surfaces B: Biointerfaces. 2011;85(2):360-365. DOI:10.1016/j.colsurfb.2011.03.009

[82] Munir H, Mumtaz A, Rashid R, Najeeb J, Zubair MT, Munir S, Bilal M, Cheng H. Eucalyptus camaldulensis gum as a green matrix to fabrication of zinc and silver nanoparticles: Characterization and novel prospects as antimicrobial and dye-degrading agents. Journal of Materials Research and Technology. 2020;9(6):15513-15524. DOI:10.1016/j.jmrt.2020.11.026

[83] Rasheed T, Bilal M, Iqbal HMN, Li C. Green biosynthesis of silver nanoparticles using leaves extract of Artemisia vulgaris and their potential biomedical applications. Colloids and Surfaces B: Biointerfaces. 2017;158:408-415. DOI:10.1016/j.colsurfb.2017.07.020

[84] Nakkala JR, Mata R, Gupta AK, Sadras SR. Biological activities of green silver nanoparticles synthesized with Acorous calamus rhizome extract. European Journal of Medicinal Chemistry. 2014;85:784-794. DOI:10.1016/j.ejmech.2014.08.024

[85] Zargar M, Hamid AA, Bakar FA, Shamsudin MN, Shameli K, Jahanshiri F, Farahani F. Green Synthesis and antibacterial effect of silver nanoparticles using vitex

negundo L. Molecules. 2011;16(8):6667-6676.doi:10.3390/molecules16086667

[86] Khan ZUH, Shah NS, Iqbal J, Khan AU, Imran M, Alshehri SM, et al. Biomedical and photocatalytic applications of biosynthesized silver nanoparticles: Ecotoxicology study of brilliant green dye and its mechanistic degradation pathways. Journal of Molecular Liquids. 2020;319:114114. DOI:10.1016/j.molliq.2020.114114

[87] Unser S, Bruzas I, He J, Sagle L. Localized Surface Plasmon Resonance Biosensing: Current Challenges and Approaches. Sensors. 2015;15(7):15684-15716. DOI:10.3390/s150715684

[88] Cao Z, He P, Huang T, Yang S, Han S, Wang X, Ding G. Plasmonic Coupling of AgNPs near Graphene Edges: A Cross-Section Strategy for High-Performance SERS Sensing. Chemistry of Materials. 2020;32(9):3813-3822. DOI:10.1021/acs.chemmater.9b05293

[89] Ashraf JM, Ansari MA, Khan HM, Alzohairy MA, Choi I. Green synthesis of silver nanoparticles and characterization of their inhibitory effects on AGEs formation using biophysical techniques. Scientific Reports. 2016;6(1). DOI:10.1038/srep20414

[90] Loiseau A, Asila V, Boitel-Aullen G, Lam M, Salmain M, Boujday S. Silver-Based Plasmonic Nanoparticles for and Their Use in Biosensing. Biosensors. 2019;9(2):78. DOI:10.3390/bios9020078

[91] Wang X, Hou T, Lin H, Lv W, Li H, Li F. In situ template generation of silver nanoparticles as amplification tags for ultrasensitive surface plasmon resonance biosensing of microRNA. Biosensors and Bioelectronics. 2019;137:82-87. DOI:10.1016/j.bios.2019.05.006

[92] Wang X, Wu L, Ren J, Miyoshi D, Sugimoto N, Qu X. Label-free colorimetric and quantitative detection of cancer marker protein using noncrosslinking aggregation of Au/Ag nanoparticles induced by target-specific peptide probe. Biosensors and Bioelectronics. 2011;26(12):4804-4809. DOI:10.1016/j.bios.2011.06.012

[93] Bahavarnia F, Pashazadeh-Panahi P, Hasanzadeh M, Razmi N. DNA based biosensing of Acinetobacter baumannii using nanoparticles aggregation method. Heliyon. 2020;6(7):1-6. DOI:10.1016/j.heliyon.2020.e04474

[94] Wang WF, Qiang Y, Meng XH, Yang JL, Shi YP. Ultrasensitive colorimetric assay melamine based on in situ reduction to formation of CQDs-silver nanocomposite. Sensors and Actuators B: Chemical. 2018;260:808-815. DOI:10.1016/j.snb.2018.01.108

[95] Rajamanikandan R, Ilanchelian M. Simple and visual approach for highly selective biosensing of vitamin B1 based on glutathione coated silver nanoparticles as a colorimetric probe. Sensors and Actuators B: Chemical. 2017;244:380-386. DOI:10.1016/j.snb.2016.12.129

[96] Guo Y, Wu J, Li J, Ju H. A plasmonic colorimetric strategy for biosensing through enzyme guided growth of silver nanoparticles on gold nanostars. Biosensors and Bioelectronics. 2016;78:267-273. DOI:10.1016/j.bios.2015.11.056

[97] Barghouti ME, Akjouj A, Mir A. Design of silver nanoparticles with graphene coatings layers used for LSPR biosensor applications. Vacuum. 2020;180:1-23. DOI:10.1016/j.vacuum.2020.109497

[98] Tang J, Xiong P, Cheng Y, Chen Y, Peng S, Zhu ZQ. Enzymatic oxydate-triggered AgNPs etching: A novel signal-on photoelectrochemical

immunosensing platform based on Ag@AgCl nanocubes loaded RGO plasmonic heterostructure. Biosensors and Bioelectronics. 2019;130:125-131. DOI:10.1016/j.bios.2019.01.014

[99] Wang Y, Li Z, Li H, Vuki M, Xu D, Chen HY. A novel aptasensor based on silver nanoparticle enhanced fluorescence. Biosensors and Bioelectronics. 2012;32(1):76-81. DOI:10.1016/j.bios.2011.11.030

[100] Sangappa Y, Latha S, Asha S, Sindhu P, Parushuram N, Shilpa M, Byrappa K, Narayana B. Synthesis of anisotropic silver nanoparticles using silk fibroin: characterization and antimicrobial properties. Materials Research Innovations. 2017;23(2):79-85. DOI:10.1080/14328917.2017.1383680

[101] Wu Q, Si M, Zhang B, Zhang K, Li H, Mi L, et al. Strong damping of the localized surface plasmon resonance of Ag nanoparticles by Ag2O. Nanotechnology. 2018;29(29):1-18. DOI:10.1088/1361- 6528/aac031

[102] Mlalila N, Swai H, Hilonga A, Kadam D. Antimicrobial dependence of silver nanoparticles on surface plasmon resonance bands against Escherichia coli. Nanotechnology, Science and Applications. 201610:1-9. DOI:10.2147/nsa.s123681

[103] Ribeiro MS, de Melo LSA, Farooq S, Baptista A, Kato IT, Núñez SC, et al. Photodynamic inactivation assisted by localized surface plasmon resonance of silver nanoparticles: In vitro evaluation on *Escherichia coli* and *Streptococcus mutans*. Photodiagnosis and Photodynamic Therapy. 2018;22:191-196. DOI:10.1016/j.pdpdt.2018.04.007

[104] Louis C, Pluchery O. Gold Nanoparticles for Physics, Chemistry and Biology. 1st ed. London: Imperial College Press; 2012. 308 p. DOI:10.1142/p815

[105] Ahn H, Song H, ryul Choi J, Kim K. A localized surface plasmon resonance sensor using double-metal-complex nanostructures and a review of recent approaches. Sensors. 2017;18(2):1-20. DOI:10.3390/s18010098

[106] Caro C, M P, Klippstein R, Pozo D, P A. Silver Nanoparticles: Sensing and Imaging Applications. In: Perez DP, editor. Silver Nanoparticles. London: InTech; 2010. p. 201-223. DOI:10.5772/8513

[107] Liu B, Zhuang J, Wei G. Recent advances in the design of colorimetric sensors for environmental monitoring. Environmental Science: Nano. 2020;7(8):2195-2213. DOI:10.1039/d0en00449a

[108] Anker JN, Hall WP, Lyandres O, Shah NC, Zhao J, Van Duyne RP. Biosensing with plasmonic nanosensors. In: Rodgers P, editor. Nanoscience and Technology: A Collection of Reviews from Nature Journals. CoPublished with Macmillan Publishers Ltd, UK; 2010. p. 308-319. DOI:10.1142/9789814287005 0032

[109] Oh SY, Heo NS, Bajpai VK, Jang SC, Ok G, Cho Y, et al. Development of a Cuvette-Based LSPR Sensor Chip Using a Plasmonically Active Transparent Strip. Frontiers in Bioengineering and Biotechnology. 2019;7:1-11. DOI:10.3389/fbioe.2019.00299

[110] Bastos V, de Oliveira JMPF, Brown D, Jonhston H, Malheiro E, da Silva ALD, et al. The influence of Citrate or PEG coating on silver nanoparticle toxicity to a human keratinocyte cell line. Toxicology Letters. 2016;249:29-41. DOI:10.1016/j.toxlet.2016.03.005

[111] Pinzaru I, Coricovac D, Dehelean C, Moacã EA, Mioc M, Baderca F, et al. Stable PEG-coated silver nanoparticles – A comprehensive toxicological profile. Food and

Chemical Toxicology. 2018;111:546-556. DOI:10.1016/j.fct.2017.11.051

[112] Devi JM, Umadevi M. Synthesis and Characterization of Silver–PVA Nanocomposite for Sensor and Antibacterial Applications. Journal of Cluster Science. 2013;25(2):639-650. DOI:10.1007/s10876-013- 0660-6

[113] Haberl N, Hirn S, Wenk A, Diendorf J, Epple M, Johnston BD, et al. Cytotoxic and proinflammatory effects of PVP-coated silver nanoparticles after intratracheal instillation in rats. Beilstein Journal of Nanotechnology. 2013;4:933-940. DOI:10.3762/bjnano.4.105

[114] Ban DK, Paul S. Rapid colorimetric and spectroscopy based sensing of heavy metal and cellular free oxygen radical by surface functionalized silver nanoparticles. Applied Surface Science. 2018;458:245-251. DOI:10.1016/j.apsusc.2018.07.069

[115] Faghiri F, Ghorbani F. Colorimetric and naked eye detection of trace Hg^{2+} ions in the environmental water samples based on plasmonic response of sodium alginate impregnated by silver nanoparticles. Journal of Hazardous Materials. 2019;374:329-340. DOI:10.1016/j.jhazmat.2019.04.052

[116] Ranjani B, Pandian K, Kumar GA, Gopinath SCB. D-glucosamine chitosan base molecule-assisted synthesis of different shape and sized silver nanoparticles by a single pot method: A greener approach for sensor and microbial applications. International Journal of Biological Macromolecules. 2019;133:1280-1287. DOI:10.1016/j.ijbiomac.2019.04.196

[117] Rezaei ZB, Rastegarzadeh S, Kiasat A. In-situ decorated silver nanoparticles on electrospun poly (vinyl alcohol)/chitosan nanofibers as a plasmonic sensor for azathioprine determination. Colloids and Surfaces A: Physicochemical and Engineering Aspects. 2018;559:266-274. DOI:10.1016/j.colsurfa.2018.09.047

[118] Yilmaz H, Cobandede Z, Yilmaz D, Cinkilic A, Culha M, Demiralay EC. Monitoring forced degradation of drugs using silica coated AgNPs with surface-enhanced Raman scattering. Talanta. 2020;214:1-8. DOI:10.1016/j.talanta.2020.120828

[119] Sharma VK, Yngard RA, Lin Y. Silver nanoparticles: Green synthesis and their antimicrobial activities. Advances in Colloid and Interface Science. 2009;145(1-2):83-96. DOI:10.1016/j.cis.2008.09.002

[120] Kurbanoglu S, Ozkan SA, Merkoc¸i A. Nanomaterials-based enzyme electrochemical biosensors operating through inhibition for biosensing applications. Biosensors and Bioelectronics. 2017;89:886-898. DOI:10.1016/j.bios.2016.09.102

[121] Meng F, Sun H, Huang Y, Tang Y, Chen Q, Miao P. Peptide cleavage-based electrochemical biosensor coupling graphene oxide and silver nanoparticles. Analytica Chimica Acta. 2019;1047:45-51. DOI:10.1016/j.aca.2018.09.053

[122] Chisanga M, Muhamadali H, Ellis D, Goodacre R. Enhancing Disease Diagnosis: Biomedical Applications of Surface-Enhanced Raman Scattering. Applied Sciences. 2019;9(6):1163. DOI:10.3390/app9061163

[123] Kucherenko IS, Soldatkin OO, Kucherenko DY, Soldatkina OV, Dzyadevych SV. Advances in nanomaterial application in enzyme-based electrochemical biosensors: a review. Nanoscale Advances. 2019;1(12):4560-4577. DOI:10.1039/c9na00491b