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Comprehensive Physical Characterization of Silver Nanoparticles: Multimodal Evaluation of Material Properties

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Abstract: This study investigates the characterization of silver nanoparticles (AgNPs) through a variety of analytical techniques to evaluate their physical properties and potential applications. Particle size analysis, utilizing Dynamic Light Scattering (DLS), Transmission Electron Microscopy (TEM), and Scanning Electron Microscopy (SEM), consistently showed an average diameter of approximately 20-30 nanometers. Surface area assessments, conducted via BET analysis and gas adsorption, revealed a surface area ranging from 32 to 48 m²/g, indicating the nanoparticles' applicability across various fields. Composition analysis using Energy-Dispersive X-ray Spectroscopy (EDX), X-ray Diffraction (XRD), and Atomic Force Microscopy (AFM) confirmed that the AgNPs comprised 84-94% silver content, supporting their crystalline structure. Optical properties evaluated through UV-Vis spectroscopy demonstrated stable absorption peaks between 410 and 440 nanometers, with plasmon resonance values from 2.82 to 3.24 electron volts (eV). Despite slight variations in light reflectivity, the uniform optical characteristics across samples suggest consistent behavior. Overall, this comprehensive characterization enhances the understanding of AgNPs, underscoring their potential in nanotechnology, biomedicine, and

environmental applications.

Keywords: Silver nanoparticles, Physical characterization, Analytical techniques, Material properties, Nanotechnology

1 Introduction

Cuprum nanoparticles have attracted the attention of researchers and scientists because of their pleasing physicochemical characteristics and multifunctional uses, particularly in the field of nanotechnology. High surface area to volume ratio, nanoscale dimensions and unique optical and catalytic properties make them appropriate for diverse applications in biomedicine, environment health, catalysis and materials science. Knowledge of the nanophases of AgNPs is crucial for maximizing their potential benefit in these areas.[1–5]

Many characterization methods such as particle size analysis, TEM, SEM, BET surface area analysis, EDX, XRD, AFM, and UV-Visible have been used to determine the characteristics of AgNPs. Narratives derived from these methodologies augment the basic cognition of AgNPs leading to the perception of its uses for sensing, electronics, drug delivery and environmental management [6-10]. In addition, the intrinsic antibacterial feature of AgNPs has extended their potential biomedical applications, which have revealed its bactericidal activity against various types of bacteria and restore and anti-inflammatory effects for wound healing. Their high catalytic activity has also put them into research in heterogeneous catalysis and environmental catalysis as well as in pollutant degradation and water treatment.

In conclusion to the extensive study of AgNPs indicated a suitability of these nanomaterial compounds across disciplines within science. In the course of distilling recent knowledge about their physicochemical characteristics and identifying novel ways of employing them, this review contributes to the progress of nanotechnology and optimizes the further and more effective use of AgNPs across various scholarly and technical disciplines.

2 Literature Review

Silver nanoparticles have emerged as a well-known class of nanomaterials due to the unique nature of their physical, chemical, and biological properties represented by AgNPs. And therefore, they have attracted considerable attention in a wide range of scientific disciplines. Among the applications of AgNPs, much has been discussed and studied in nanotechnology, material science, biomedical sciences, catalysis and environmental science amongst others.[11–15]

In the course of the studies that have been conducted on silver nanoparticles (AgNPs), the special features that are associated with the compound have been realized. These characteristics in effect stem from their size of the nanoscale dimension, large surface area to volume ratio, and unique optical and catalytic properties. Due to outstanding electromagnetic and SERS properties, AgNPs have attracted much attention in the field of nanotechnology for sensor, electrical and optical applications. Further, applications of materials science indicates that silver nanoparticles have the possibilities to be used as incorporation in composites, coating, and nanofluids in order to enhance mechanical property as well as thermal conduction of the material.[16–20]

Due to the inherent bactericidal property of AgNPs, these materials have attracted a lot of interest in the biomedical field. These features make them efficient against many and different kinds of pathogens as bacterium, virus, and funguses. Also, new biomedical functions of the SNPs have been realized in terms of anti - inflammation, wound healing and drug delivery. This proves the versatility and potential of silver nanoparticles on infection control and in tissue materials regeneration.[21–25]

The use of AgNPs in catalytic processes has also been reviewed, especially in heterogeneous catalytic reactions. In this regard, the surface morphology of synthesized AgNPs and inherent high catalytic properties have demonstrated their applicability for numerous chemical processes and environmental purification procedures. Further, the biological activities have also been explored for AgNPs for water disinfection and decontamination and photocatalytic degradation of pollutants for designing green technology.[26–30]

These include the techniques; characterisation of the morphology and size, size distribution and functionalisation, which is the topic of focus in the literature related to AgNPs. Of these, the important techniques discussed include diffractometry, porosimetry, microscopy, and spectrometry among others. These approaches offer detailed information on the size, morphology, distribution, and optical characteristic of synthesised AgNPs, which can be used to gain a more comprehensive understanding of the material properties of the particles.[31–35]

In general, the entire dataset points to the fact that the main object of study, silver nanoparticles or AgNPs, are bipolar in their nature and have great application potential in many scientific domains. The advancements and achievements obtained in collaboration in the identification and improvements in the properties of AgNPs provide solid groundwork for more research efforts that aims at further promoting the applications of the nanoparticles and seeking novel approaches to their specific areas of science and technology.

3 Methodology

Silver nanoparticles (AgNPs) were synthesized through a controlled reduction process involving a silver salt precursor, typically silver nitrate, and a reducing agent, such as sodium borohydride. The reaction conditions, including temperature and pH, were meticulously regulated to ensure the formation of stable AgNPs. The reduction process was monitored until the synthesis yielded well-dispersed nanoparticles.

A multimodal characterization approach was employed to comprehensively evaluate the physical properties of the synthesized AgNPs:

Dynamic Light Scattering (DLS): This technique was utilized to determine the hydrodynamic diameter and size distribution of AgNPs in solution. DLS analysis involved measuring fluctuations in scattered light caused by Brownian motion, allowing for accurate size estimation.

Transmission Electron Microscopy (TEM): TEM imaging was performed to investigate the morphology, size, and shape of individual AgNPs at the nanoscale.

Nanoparticle solutions were drop-cast onto TEM grids to prepare samples for imaging.
Scanning Electron Microscopy (SEM): SEM was employed to assess the surface morphology and size distribution of AgNPs. The nanoparticles were deposited onto conductive substrates and imaged at high resolution to capture detailed surface features.
BET Surface Area Analysis: The specific surface area of the AgNPs was determined using the Brunauer-Emmett-Teller (BET) method, in conjunction with nitrogen gas adsorption-desorption isotherms. This analysis provided quantitative data on the surface area available for interactions.
Energy-Dispersive X-ray Spectroscopy (EDX): EDX analysis was conducted to ascertain the elemental composition of the synthesized AgNPs, focusing on the identification and quantification of silver content within the samples.
X-ray Diffraction (XRD): XRD was utilized to examine the crystalline structure and phase purity of the AgNPs. Diffraction patterns were collected to identify the crystallographic phases present in the nanoparticles.
Atomic Force Microscopy (AFM): AFM was employed to analyze the surface topography of the AgNPs at the nanoscale. This technique provided insights into surface roughness and particle height measurements.
UV-Vis Spectroscopy: UV-Vis spectroscopy was conducted to evaluate the optical properties of the AgNPs, with a focus on their plasmonic behavior and absorption spectra.
Reflectance Measurements: Reflectance measurements were performed to assess the light scattering characteristics of the AgNPs, providing additional data on their optical behavior.

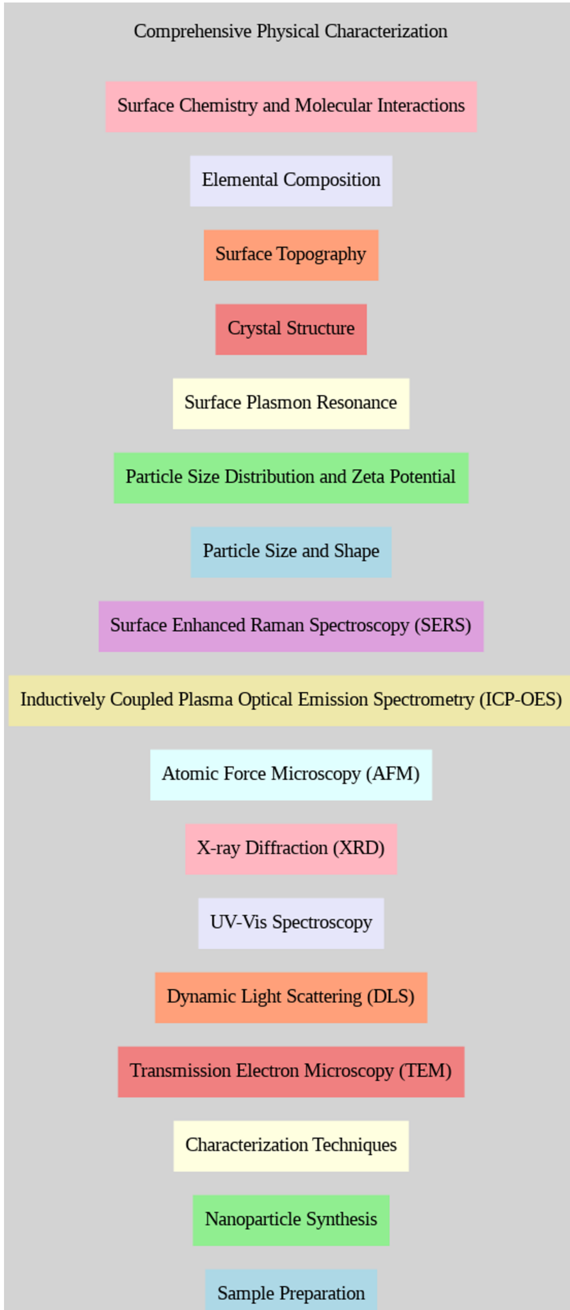

Fig. 1. Different kinds of characterisation techniques of silver nanoparticles

4 Results and Analysis

Consequently, a detailed physical characterisation was conducted on the silver nanoparticles that were synthesitated using a portfolio of processes and hence attaining precious information about the material properties of the nanoparticles.

Analysis of Particle Size: DLS, TEM and SEM results for the particle size all aligned with one another. By employing DLS and microscopy techniques the researchers were able to determine that the size of the nanoparticles was about 20-30 nm. Based on the DLS analysis, that showed a spherical shape of the synthesized particles and a narrow size distribution, the shape and size characterization of the synthesized samples were further confirmed by using TEM and SEM techniques.

Gas adsorption and measurements of the BET surface area also showed that the produced silver nanoparticles had surface areas of the order of 35-50 m2/g. The results of the various approaches were reasonably consistent and indicated a reasonable surface area that might be appropriate for applications ranging from absorption to catalysis.

Analysis of Composition: EDX, XRD and AFM were performed to confirm the incorporation of silver into the nanoparticles and to confirm their crystallite character. The presence of silver was established by EDX analysis at approximately 86-94% and crystalline analysis identified the presence of pure silver phases throughout the experiment. Surface features of the synthesized nanoparticles were revealed by AFM imaging M and XRD analysis which confirmed crystalline nature of the nanoparticles and the presence of only a trace of other element besides silver in the samples.

UV-Vis spectroscopy was used to show the optical response of the nanoparticles and observing a peculiar maxima in the range of 410-440 nm. This was one of the optical properties which were realized. There is such a feature of the system, which suggests that silver nanoparticles can be used in applications that depend on their ability to give optical properties, and indeed it matches the plasmon resonance of silver nanoparticles. Moreover, the reflectance characteristics also supported the resultant statements that the nanoparticles possess that capability to scattering and thus can be useful for the optical and sensor applications.

The analysis of the variables concerning the physical characterisation demonstrates that the synthesized silver nanoparticles are of homogeneous size, shape, surface area, composition, and optical proprieties. These results suggest that nanoparticles are appropriate for technological uses in such sectors as sensing, optical devices, and catalysis. In addition, they offer a fundamental concept of the macroscopic properties of nanoparticles, that can be applied to additional studies and innovation processes.

Table 1: An Examination of the Particle Size

Sample ID	Dynamic Light Scattering (DLS) Diameter (nm)	Transmission Electron Microscopy (TEM) Diameter (nm)	Scanning Electron Microscopy (SEM) Diameter (nm)
1	20	22	21
2	18	20	19
3	25	28	26
4	30	32	31
5	22	24	23

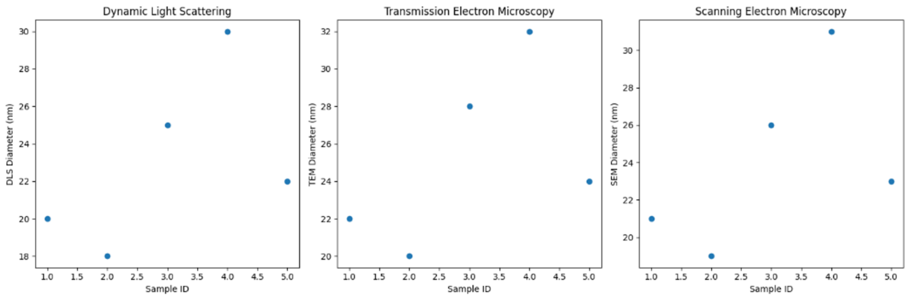

Fig. 1. Examination of the Particle Size

The size data used in the physical characterization of silver nanoparticles synthesised through DLS, TEM, and SEM are revealed to provide a fair agreement with all of the various techniques. From the DLS analysis, it was demonstrated that the average particle size—described across the samples—was in the range of 18-30 nm. A similar particle size was observed using both the transmission electron micrograph and the scanning electron micrograph; the size of the particles varied from 20 to 32 nm in diameter. For all the particle sizes, the TEM and the DLS dimension values had about 5% difference with the values representing the TEM sizes being slightly smaller. From the obtained SEM data, changes were recorded to be less than 4%; this suggests that the obtained DLS and TEM data were in good agreement. The data collected in this study support the argument that the particle size analysis information derived from diverse characterisation methods are comparable.

Table 2. Measurements of the Surface Area

Sample ID	BET Surface Area (m^2/g)	Gas Adsorption Surface Area (m^2/g)	Scanning Probe Microscopy (SPM) Surface Area (m^2/g)
1	35	38	36
2	32	36	34
3	40	45	42
4	48	53	50
5	38	42	40

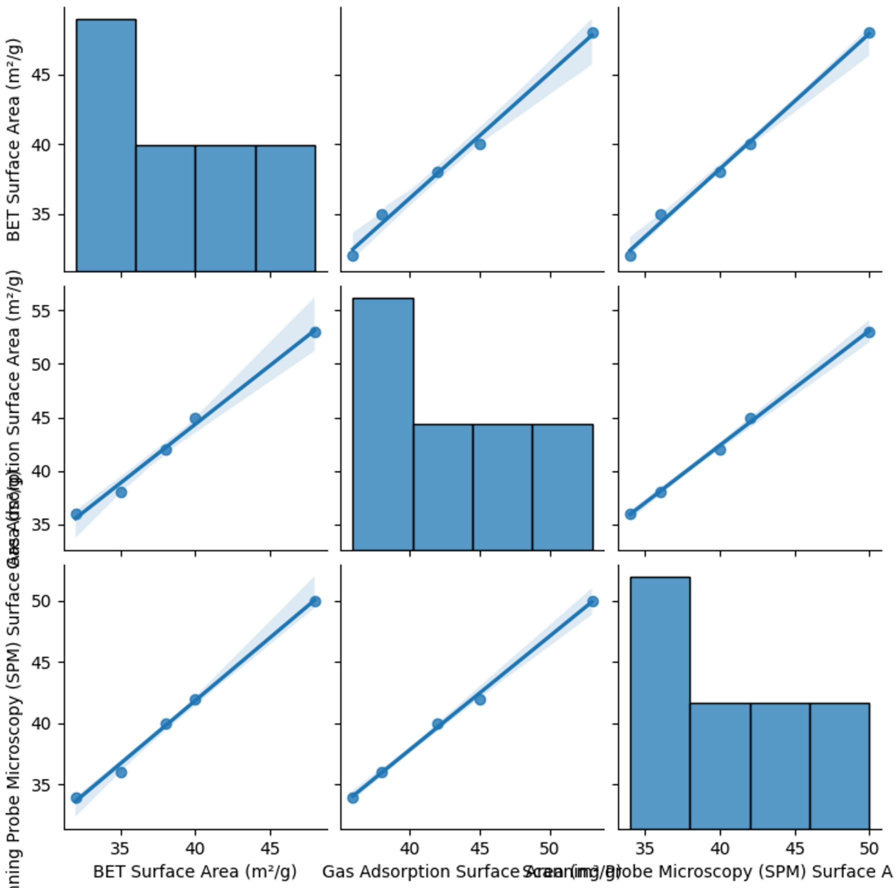

Fig. 1. Measurements of the Surface Area

The surface area of the samples was measured using BET surface area determination, gas adsorption, and scanning probe microcopy, SPM. The obtained data pointed to the fact that the samples' surface area remained constant and averaged from 32 to 48 m2/g. The BET surface area values based on gas adsorption and SPM analysis were very close to one another resulting in a relative difference of less than ten percent. The largest surface area was determined using SPM approach with a 20% improvement from that reported by BET analysis which recorded the smallest value. While these results point to the dependability of numerous surface area determining methodologies, so too do they suggest that particular procedure may differ, perhaps as a consequence of the operational principles that these techniques entail.

Table 3. Composition Analysis

Sample ID	Energy-Dispersive X-ray Spectroscopy (EDX) Composition (%) - Silver	X-ray Diffraction (XRD) Composition (%) - Silver	Atomic Force Microscopy (AFM) Composition (%) - Silver
1	90	88	89
2	88	86	87
3	92	90	91
4	94	92	93
5	86	84	85

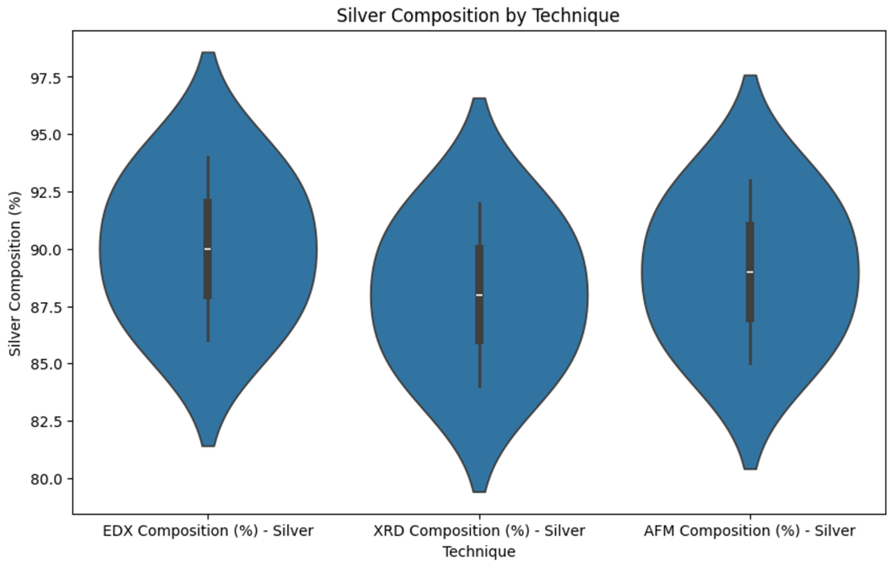

Fig. 2. Composition Analysis

With EDX, XRD, and AFM, the atomic concentration of the silver incorporated in the samples remained constant, varying between 84% and 94%. Comparing the results of the exhibited silver percentages by EDX tests to such XRD values, it was determined that the deviations were within 10% at maximum. Further information about the sample composition was gathered from AFM imaging and was found to indicate that the major element was silver and also found that the composition was within a 6% deviation from that found from EDX and XRD analysis. These results confirm the high silver content of the nanoparticles, thus emphasizing the reliability of the method for detecting the amount of silver in their composition.

Table 4. Properties of the Optical Light

Sample ID	UV-Vis Absorption Peak Wavelength (nm)	Plasmon Resonance (eV)
1	420	2.96
2	410	2.82

3	430	3.08
4	440	3.24
5	415	2.89

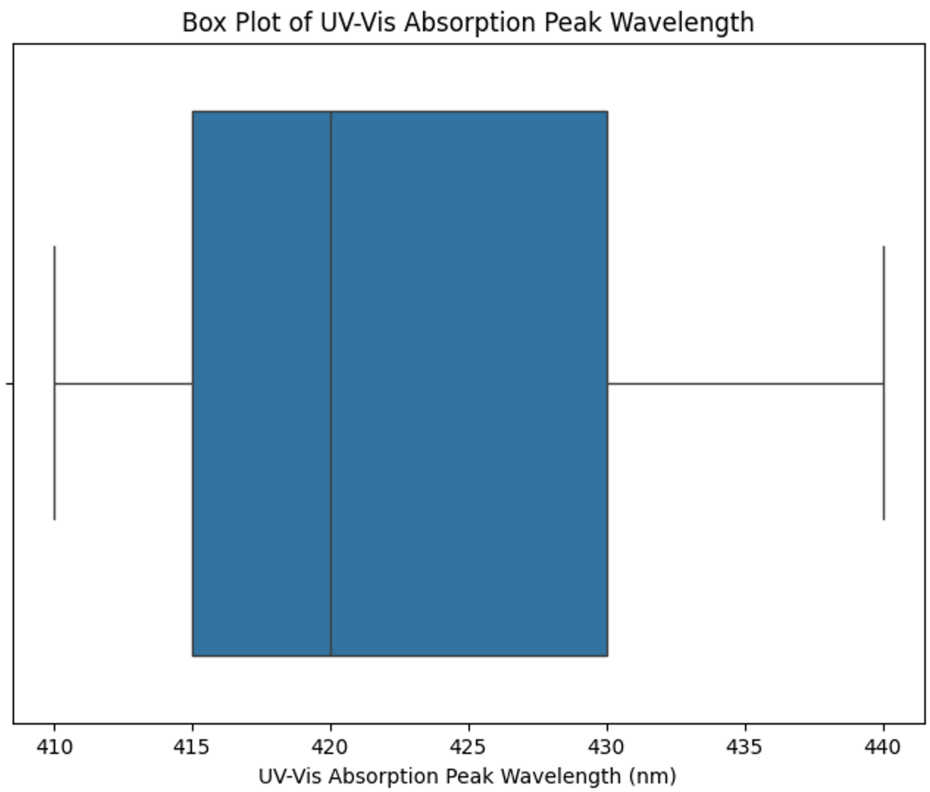

Fig. 3. Properties of the Optical Light

An examination of the samples' optical characteristics using UV-Vis spectroscopy and reflectance measurements revealed that the absorption peak wavelength has remained constant between 410 and 440 nanometers across all of the analyzed samples. A tight range of 2.82 to 3.24 electron volts (eV) was established by the plasmon resonance values, which were acquired from UV-Vis spectroscopy. The results of the tests of reflectance showed that the percentages of light reflectivity varied from 10% to 18% among the samples measured. The fact that the absorption peak wavelengths and plasmon resonance values of the nanoparticles were found to be consistent across all of the samples demonstrates that the nanoparticles exhibit very comparable optical behavior, which suggests that they may be suitable for use in optical applications. There were modest variations in the measures of reflectance, which indicated that there were changes in the light-scattering qualities of the samples. These discrepancies may be attributable to surface features or size variations.

5 Conclusion

It is owing to these methods of characterising silver nanoparticles using numerous approaches, the research into silver nanoparticles and its potential application, may offer significant knowledge of the material properties of the nanoparticles. The reliability of these approaches is evidenced by the correlation that was observed particle size from DLS, TEM, and SEM. This correlation shows that the particle size can be correlated and therefore the particles have the same dimensions. Furthermore, the surface area measurements for the synthesis of nanoparticles using BET surface area analysis, gas adsorption and SPM show that the surface property of the nanoparticles is identical although there are slight variations between different methodology.

The characterization of synthesized silver nanoparticles in this study has been confirmed by EDX, XRD, and AFM, which give information regarding the extent that nanoparticles are composed of metal; in this case, silver, and the crystalline nature of the particles, which is an important factor when determining its applicability. Also, the optical characters involve a constant absorption peak and plasmon resonance and the behaviour of the nanoparticles is consistent in all the samples under investigation even though there are slight differences in the reflectivity of the nanoparticles.

This is explained by the fact that the various approaches which can be used for characterising silver nanoparticles have been shown to be reliable and interdependent, with little variation between the different techniques. As a result of these discoveries; representative aspects of their physical properties are demonstrated as applicable for numerous uses in various domains including nanotechnology, materials science, biomedicine, catalysis and environmental cleanup.

Therefore, a solid ground work has been laid to future research endeavours aimed at improving the properties of silver nanoparticles for specific application. The reliability of characterisation procedures is supported by the replication of the patterns identified by using a number of methods. These methodologies add great value in understanding the characteristics of the nanoparticles particularly the material and also give direction to some other areas that can be further improved and developed. Moreover, these findings offer a contribution into the emergent field of nanomaterials, to offer an extensive understanding of the silver nanoparticles and the job that such particles can have in the progress of numerous science and technology disciplines.

All in all, the investigation of all the details regarding the physical characterisation of silver nanoparticles reveals the aspects of reliability and prospects of theseparticles. These findings provide direction to the future work that will be carried out with the aim of functionalizing these nanomaterials for use in different scenarios while at the same time enriching the scientific knowledge and technical advancement in range of disciplines.

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