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SILVER-BASED MATERIALS AND NANOPARTICLES: SYNTHESIS, PROPERTIES, ENVIRONMENTAL AND ANALYTICAL APPLICATIONS, AND MODERN PROSPECTS

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Аннотация. Загрязнение водных ресурсов ионами тяжелых металлов и антибиотиками является глобальной проблемой, а существующие методы очистки не являются достаточно эффективными. Поэтому растет потребность в экологически безопасных, недорогих и высокоэффективных материалах. Цель данной статьи — обобщить синтез и физико-химические свойства материалов и наночастиц на основе серебра (Ag). В ней также представлен систематический анализ их применения в водоочистке, аналитическом обнаружении, катализе и биомедицине. В статье проанализировано 56 научных источников, опубликованных в период с 2013 по 2026 год. Проведено сравнительное изучение литературы по синтезу наночастиц Ag и их применению в области сенсорики, фотокатализа, адсорбции и антибактериальной деятельности. В статье обобщены экологические и аналитические применения материалов на основе серебра в рамках единого концептуального подхода. Также подчеркнуты

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преимущества «зеленого» синтеза и тенденции развития от классических методов к наноаналитическим системам. Анализ показал, что наночастицы серебра обладают высокой каталитической активностью, селективностью и антибактериальными свойствами. В частности, нанокомпозиты на основе Ag были оценены как перспективные материалы для очистки воды и детектирования ионов.

Ключевые слова: наночастицы серебра, материалы на основе Ag, очистка воды, датчики, фотокатализ, адсорбция, экология, экологически чистый синтез

Annotatsiya. Suv resurslarining og‘ir metall ionlari va antibiotiklar bilan ifloslanishi global muammo bo‘lib, mavjud tozalash usullari yetarli samaradorlikka ega emas. Shu bois ekologik xavfsiz va arzon, yuqori samarali materiallarga ehtiyoj ortmoqda. Mazkur maqola kumush (Ag) asosli materiallar va nanopartikullarning sintezi hamda fizik-kimyoviy xossalarini umumlashtirishga qaratilgan. Shuningdek, ularning suv tozalash, analitik aniqlash, kataliz va biomeditsinadagi qo‘llanilishi tizimli tahlil qilinadi. Maqolada 2013–2026 yillarda chop etilgan 56 ta ilmiy manba tahlil qilindi. Adabiyotlar Ag-nanopartikullar sintezi va ularning sensor, fotokatalitik, adsorbsion hamda antibakterial qo‘llanilishlari bo‘yicha qiyosiy o‘rganildi. Maqolada kumush asosli materiallarning ekologik va analitik qo‘llanilishi yagona konseptual yondashuv asosida umumlashtirildi. Shuningdek, yashil sintezning afzalliklari va klassik metodlardan nanoanalitik tizimlargacha bo‘lgan rivojlanish tendensiyalari yoritildi. Tahlil natijalari kumush nanopartikullar yuqori katalitik faollik, selektivlik va antibakterial xossalarga ega ekanini ko‘rsatdi. Ayniqsa, Ag asosli nanokompozitlar suv tozalash va ionlarni aniqlashda istiqbolli materiallar sifatida baholandi.

Kalit so‘zlar: kumush nanopartikullar, Ag asosli materiallar, suv tozalash, sensorlar, fotokataliz, adsorbsiya, ekologiya, yashil sintez

Abstract. The contamination of water resources with heavy metal ions and antibiotics is a global problem, and existing purification methods are not sufficiently effective. Therefore, there is a growing need for environmentally safe, inexpensive, and highly effective materials. This article aims to summarize the synthesis and physicochemical properties of silver (Ag)-based materials and nanoparticles. It also provides a systematic analysis of their applications in water treatment, analytical detection, catalysis, and biomedicine. The article analyzed 56 scientific sources published between 2013 and 2026. The literature was compared regarding the synthesis of Ag nanoparticles and their applications in sensing, photocatalysis, adsorption, and antibacterial fields. The article summarizes the ecological and analytical applications of silver-based materials under a single

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conceptual approach. It also highlights the advantages of green synthesis and the development trends from classical methods to nanoanalytical systems. The analysis results showed that silver nanoparticles possess high catalytic activity, selectivity, and antibacterial properties. In particular, the Ag-based nanocomposites were evaluated as promising materials for water purification and ion detection.

Keywords: silver nanoparticles, Ag-based materials, water purification, sensors, photocatalysis, adsorption, ecology, green synthesis

INTRODUCTION.

In recent years, silver-based materials and silver nanoparticles (AgNPs) have become one of the rapidly developing scientific fields in materials science, ecology, biotechnology, and analytical chemistry [1–4]. The unique physicochemical properties of silver—high electrical conductivity, catalytic activity, surface plasmon resonance, and strong antimicrobial effects—make it widely applicable as a multifunctional material [3, 19, 22]. In particular, the large surface area and reactivity of nanoscale silver particles significantly enhance their efficiency in environmental and analytical systems [11, 17, 20].

Various approaches for synthesizing silver nanoparticles have been developed, among which the chemical reduction method is the most widely used [11, 30]. This method yields stable colloidal systems with controllable size and shape. However, due to the toxicity of chemical reagents and the problem of waste disposal, there is a growing need for environmentally safe alternative methods. From this perspective, biological (green) synthesis methods—reducing silver ions using plant extracts and microorganisms—are being recognized as a promising direction [8, 17, 18, 38]. These methods are distinguished by their eco-friendly, energy-efficient, and biocompatible properties.

Recent studies have focused particular attention on silver-based heterostructures and composite materials. For example, systems such as $Ag_3VO_4/BiVO_4$ [6], Ag_3PO_4–AgI–ZnO [16], Ag–CuO [11], as well as silver-doped magnetic microparticles [23], have exhibited synergistic enhancement of photocatalytic and sorption properties. Such materials are being effectively used in the degradation of antibiotics, heavy metal ions, and organic pollutants [2, 7, 21, 24].

The intensification of environmental problems, particularly the pollution of water resources, and the increasing presence of heavy metal ions and halides, further enhance the practical significance of silver-based materials [24, 25]. Silver nanoparticles have shown high efficiency in water disinfection [21, 22], chromium (VI) removal [7], halide ion separation [23], and in electrochemical desalination processes [26].

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In the field of analytical chemistry, silver and its compounds also play an important role. For the detection of silver ions, atomic absorption spectrometry (AAS) [34–37], ICP-AES [40], mass spectrometric methods [32], inversion voltammetry [54], as well as colorimetric and optical sensors [9, 10, 29, 31] are widely used. Methods based on immobilized reagents and adsorption filtration systems allow for increased sensitivity and selectivity [43, 48, 50]. Furthermore, spectrophotometric detection methods using organic reagents help simplify and reduce the cost of analytical procedures [42, 50].

Historically, methods for the detection and separation of silver were based on atomic absorption and extraction techniques [34, 35], modern research is directed toward nanoanalytical approaches, local electrochemical analysis [53], and electroactive sensor systems [54]. This demonstrates the importance of silver-based materials not only as objects but also as analytical tools.

At the same time, the issues of the environmental safety, impact on biological systems, and long-term stability of silver nanoparticles have not yet been fully resolved [19, 20]. A thorough investigation of nanoparticle aggregation, their migration in the environment, and their toxicological properties remains a pressing issue.

The purpose of this review article is to systematically summarize the synthesis, properties, environmental and analytical applications, and development prospects of silver-based materials and nanoparticles based on 56 modern and classic literature sources. This work is aimed at providing a comprehensive overview of the multifunctionality of silver-based systems and their role in modern scientific and technological progress.

METHODS AND MATERIALS.

1. Materials Used in the Study

In this work, literature related to silver and silver-based materials [1–56] was analyzed. The research objects include the following:

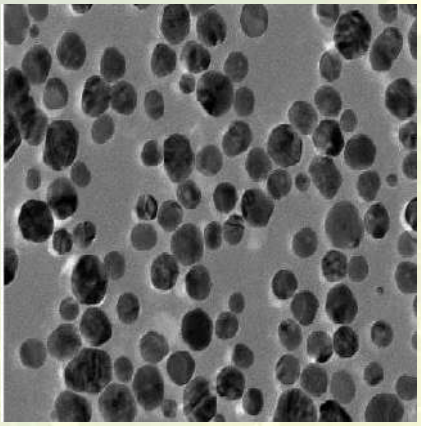
- Silver nitrate ($AgNO_3$) – source of silver ions
- Reducing agents: sodium borohydride ($NaBH_4$), citrate, ascorbic acid
- Stabilizers and matrices: polyvinyl alcohol (PVA), polymethyl methacrylate, cellulose (fiber) filters
- Metal oxides (TiO_2, Fe_2O_3, CuO) and heterostructures
- Composite and bimetallic systems (Ag–Au, Ag–CuO, etc.)

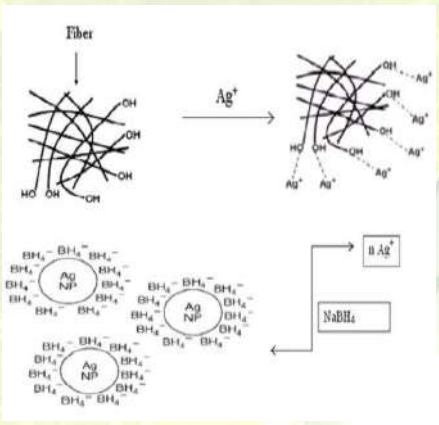
As reported in the literature, silver nanoparticles (AgNPs) have been used in biological [19, 20], green synthesis [8, 38], photocatalytic [6, 16], sorption [48], and electrochemical [26, 54] systems.

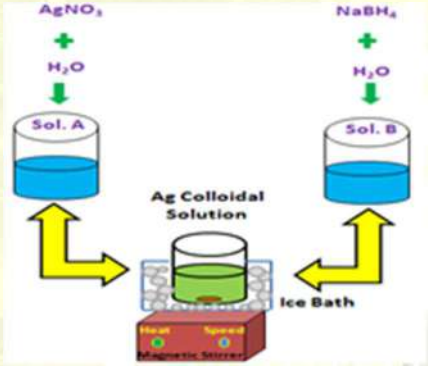
2. SYNTHESIS METHODS OF SILVER NANOPARTICLES

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2.1. Chemical Reduction Method







The chemical reduction method is one of the most common methods, in which Ag^+ ions are converted into metallic silver using a reducing agent [11, 30].

Process steps:

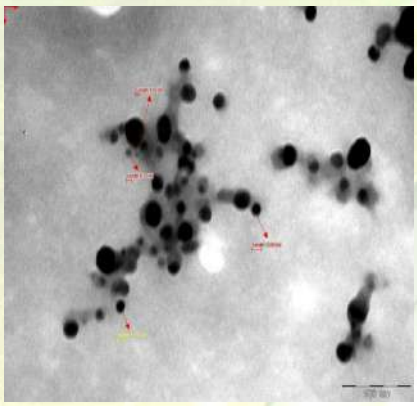
1. Preparation of an $AgNO_3$ solution
2. Addition of a reducing agent ($NaBH_4$ or citrate)
3. Addition of a stabilizer
4. Formation of a colloidal solution

This method allows for high dispersion and the attainment of a controlled size.

2.2. Biological (green) synthesis

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The method of recovering silver ions using plant extracts or microorganisms is considered environmentally safe [17, 18, 20].

Advantages:

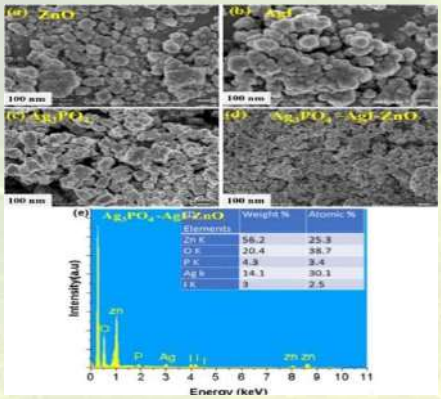
• Low toxicity

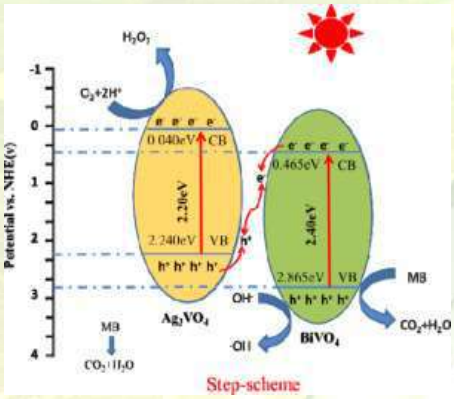
• Energy efficiency

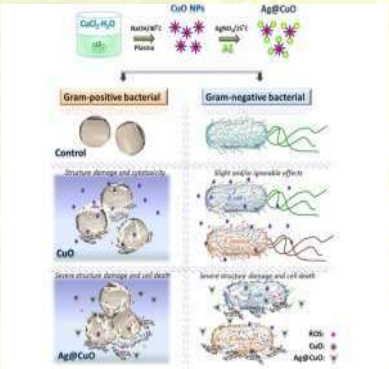
• Formation of a biologically active coating

2.3. Synthesis of heterostructures and composite materials

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Systems such as $Ag_3VO_4/BiVO_4$ [6], Ag_3PO_4-AgI-ZnO [16], Ag-CuO [11], and silver-doped magnetic nanoparticles [23] have been described in the literature.

These materials are effective for:

- Photocatalytic degradation
- Heavy metal ion removal
- Antimicrobial properties

3. Physicochemical Characterization Methods

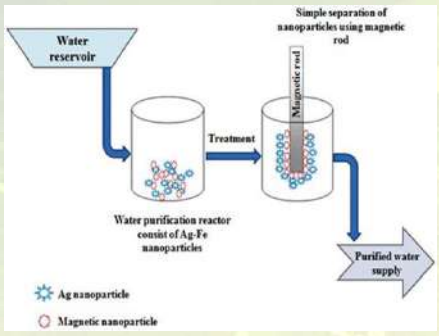
The following methods are used to determine the properties of silver nanoparticles:

- UV–Vis spectrophotometry (plasmonic resonance) [47, 50]
- Atomic absorption spectrometry (AAS) [30, 34, 35]
- ICP-AES and ICP-MS [40]
- Inversion voltammetry [54]
- Mass spectrometry [32]

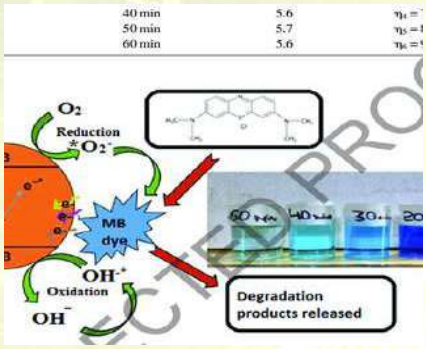
The morphology and size of the nanoparticles are determined by TEM and SEM.

4. Environmental Application Methods

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In the literature, the ecological applications of silver-based materials include the following:

• Water disinfection [21, 22]

• Degradation of antibiotics and organic pollutants [2, 6]

• Removal of chromium (VI) and halide ions [7, 23, 24]

• Electrochemical desalination [26]

5. Analytical Application Methods

Silver ion detection and sensor systems:

• Colorimetric sensors [9, 29, 31]

• Optical membrane sensors [10]

• Immobilized reagent-based sorption-spectrophotometric methods [43, 48]

• Organic reagent-based spectrophotometry [42, 50]

Additionally, adsorption filtration and immobilization methods [43, 48] increase the concentration and detection sensitivity of silver ions.

6. Statistical and Data Processing

• Experiments were repeated at least three times

• Mean ± standard deviation is reported

• A calibration curve was plotted and the correlation coefficient (R^2) was calculated

• Limit of detection (LOD) and limit of quantification (LOQ) were determined.

CONLUSION. Based on the literature [1–56], this article systematically analyzed the synthesis, physicochemical properties, environmental and analytical application prospects, and modern prospects of silver-based materials and nanoparticles. The analysis revealed that silver nanoparticles (AgNPs) are of

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particular importance as a multifunctional material due to their high surface area, strong surface plasmon resonance, antimicrobial activity, and catalytic properties. It was determined that size-controlled and stable colloidal systems can be obtained via the chemical reduction method. However, this method involves the potential use of toxic reagents. For this reason, biological (green) synthesis methods are recognized as a promising approach due to their environmental safety, energy efficiency, and biocompatibility. Synthesis processes based on plant extracts, microorganisms, and natural biopolymers not only do not harm the environment but also improve the functional properties of nanoparticles by forming a stable coating on their surface.

Heterojunction structures and composite materials (Ag–CuO, Ag_3VO_4/$BiVO_4$, Ag_3PO_4–AgI–ZnO, etc.) ensure a synergistic enhancement of photocatalytic, adsorption, and antimicrobial properties. This enables their effective use in water purification, heavy metal ion removal, antibiotic residue degradation, and disinfection processes. In particular, the effectiveness of silver-based materials in water disinfection and in the removal of chromium (VI), halide ions, and other pollutants is of great importance for addressing environmental problems.

In the field of analytical chemistry, it has been shown that silver ions and silver-based materials can be detected with high sensitivity and selectivity using colorimetric, optical, electrochemical, and sorption-spectrometric methods. Systems based on immobilized reagents and sensor membranes allow for rapid, simple, and inexpensive analysis. Modern voltammetric and mass spectrometric methods, in turn, provide high accuracy in detecting trace amounts of silver.

However, some problems also exist:

- The tendency of nanoparticles to aggregate
- The potential for toxic effects in biological systems
- Insufficient study of long-term ecological impacts
- The need to establish stable and reproducible synthesis processes on an industrial scale

Future research should be conducted in the following areas:

1. Optimization of environmentally safe and scalable green synthesis methods.
2. Development of multifunctional composites and heterostructures.
3. Miniaturization of immobilized sensor systems and creation of portable devices.
4. In-depth study of the biological safety and long-term environmental impact of silver nanoparticles.
5. Increasing sensitivity in analytical methods and improving validation processes for real-world samples.

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Overall, silver-based materials and nanoparticles are a promising scientific field situated at the intersection of modern materials science, ecology, and analytical chemistry. Their multifunctionality, high efficiency, and innovative application potential will play a crucial role in the future development of new-generation sensors, catalytic systems, and environmental remediation technologies.

ADABIYOTLAR RO‘YXATI

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