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Silver Incorporated Bio-Nanocomposite Layered Materials for Various Applications

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ABSTRACT

Silver incorporated bionanocomposite layered materials have emerged as a frontier in advanced materials science, combining the unique properties of silver nanoparticles with the versatility of layered bionanocomposite. This innovative class of materials exhibits enhanced mechanical, thermal, antimicrobial, and optical properties, making them suitable for a wide range of applications across multiple disciplines. The synthesis of these materials involves various techniques, including in-situ reduction, ex-situ incorporation, and layer-by-layer assembly, each offering distinct advantages in tailoring the final composite structure. The incorporation of silver nanoparticles into the layered bionanocomposite matrix results in materials with improved functionality, such as controlled release of antimicrobial agents, enhanced mechanical strength, and unique optical characteristics. These properties have led to their application in diverse fields, including biomedicine, where they show promise in drug delivery systems, tissue engineering scaffolds, and antimicrobial coatings; environmental remediation, particularly in water treatment and pollutant removal; food packaging, where they contribute to extended shelf life and food safety; sensing and biosensing applications, leveraging their optical and electrical properties; catalysis, where they demonstrate enhanced catalytic activity; and energy storage and conversion systems. The multifunctional nature of silver incorporated bionanocomposite layered materials addresses several contemporary challenges, from healthcare-associated infections to environmental pollution and energy efficiency. However, challenges remain in optimizing synthesis methods, ensuring uniform distribution of silver nanoparticles, and addressing potential toxicity concerns. Ongoing research focuses on improving the stability of these composites, enhancing their biocompatibility, and exploring new applications in emerging fields such as flexible electronics and smart materials. As the field continues to evolve, silver incorporated bionanocomposite layered materials hold great promise for technological advancements and innovative solutions to global challenges in healthcare, environmental protection, and sustainable development.

Introduction

The field of materials science has experienced significant advancements in recent decades, with the emergence of nanocomposites as a particularly promising area of research. Among these innovative materials, silver incorporated bionanocomposite layered materials have garnered substantial attention due to their unique properties and diverse applications. These materials represent a sophisticated integration of biological components, nanoscale materials, and the exceptional properties of silver, resulting in multifunctional composites with enhanced performance characteristics. The layered structure of these materials provides an additional dimension of functionality, allowing for controlled release mechanisms, improved mechanical properties, and increased surface area for interactions (Rhim et al., 2013; Xu et al., 2020).

Bionanocomposites, at their core, are hybrid materials that combine biological entities or biomolecules with nanostructured materials. This synergistic combination often results in properties that surpass those of the individual components. The incorporation of silver nanoparticles into these bionanocomposites further enhances their functionality, particularly in terms of antimicrobial activity, electrical conductivity, and optical properties. Silver nanoparticles have long been recognized for their broad-spectrum antimicrobial efficacy against a wide range of pathogens, including bacteria, fungi, and viruses (Rai et al., 2009). When integrated into layered bionanocomposites, these nanoparticles can provide sustained antimicrobial activity while benefiting from the structural advantages of the layered architecture.

The synthesis of silver incorporated bionanocomposite layered materials involves a variety of techniques, each offering unique advantages in terms of control over material properties and structure. These methods include in-situ reduction of silver ions within the bionanocomposite matrix, ex-situ incorporation of pre-synthesized silver nanoparticles, and layer-by-layer assembly techniques. The choice of synthesis method can significantly influence the final properties of the material, including the distribution and size of silver nanoparticles, the strength of interactions between the silver and the biopolymer matrix, and the overall stability of the composite (Zare and Shabani, 2016). Recent advancements in synthesis techniques have allowed for greater control over these parameters, enabling the tailoring of materials for specific applications.

The applications of silver incorporated bionanocomposite layered materials span a wide range of fields, showcasing their versatility and potential impact on various sectors. In the biomedical field, these materials have shown promise in wound healing, drug delivery, and tissue engineering applications. Their antimicrobial properties make them particularly suitable for developing advanced wound dressings that can prevent infection while promoting healing (Xu et al., 2020). In environmental remediation, these composites have been utilized for water purification and air filtration, leveraging the adsorptive properties of the layered structure and the antimicrobial activity of silver to remove contaminants and pathogens (Mahmoudi and Serpooshan, 2012). The food packaging industry has also benefited from these materials, with their ability to extend shelf life and maintain food quality through antimicrobial and barrier properties (Rhim et al., 2013).

Furthermore, silver incorporated bionanocomposite layered materials have found applications in sensing and biosensing technologies. The unique optical and electrical properties of silver nanoparticles, combined with the biocompatibility of the bionanocomposite matrix, make these materials excellent candidates for developing sensitive and selective sensors for various analytes, including environmental pollutants and biological markers (Zare and Shabani, 2016). In the field of catalysis, these materials have shown potential in facilitating a range of chemical reactions, benefiting from the high surface area of the layered structure and the catalytic properties of silver nanoparticles. Additionally, emerging applications in energy storage and conversion, such as in the development of advanced battery materials and photovoltaic devices, highlight the ongoing expansion of the utility of these innovative composites (Kumar et al., 2018).

As research in this field continues to evolve, new challenges and opportunities arise. Current limitations, such as the potential for silver ion leaching and long-term stability issues, are being addressed through innovative design strategies and surface modifications. Emerging trends in the field include the development of stimuli-responsive materials, the integration of multiple functional nanoparticles, and the exploration of sustainable and bio-based sources for the composite matrix. These advancements promise to further expand the applications and efficacy of silver incorporated bionanocomposite layered materials, potentially revolutionizing various technological and industrial sectors in the coming years (Xu et al., 2020; Kumar et al., 2018).

Modification of nanosilver onto different materials

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Modification of nanosilver onto graphene

The modification of nanosilver onto graphene has emerged as a significant area of research in materials science, combining the exceptional properties of both silver nanoparticles and graphene to create hybrid nanocomposites with enhanced functionality. Graphene, a two-dimensional carbon allotrope with a honeycomb lattice structure, has garnered intense scientific interest due to its remarkable mechanical strength, high electrical and thermal conductivity, and large specific surface area. These properties make graphene an ideal substrate for the deposition and stabilization of metal nanoparticles, particularly silver. The incorporation of silver nanoparticles onto graphene sheets not only preserves the intrinsic properties of both components but also often results in synergistic effects, leading to materials with superior performance in various applications (Zhu et al., 2013; Li et al., 2011).

Several methods have been developed for the modification of nanosilver onto graphene, each with its own advantages and challenges. One common approach is the in-situ reduction method, where silver ions are reduced to form nanoparticles directly on the surface of graphene or graphene oxide sheets. This method typically involves the use of reducing agents such as sodium borohydride, hydrazine, or environmentally friendly alternatives like plant extracts. For instance, Hui et al. (2014) reported a facile one-pot synthesis of silver nanoparticle-decorated reduced graphene oxide (Ag-RGO) composites using glucose as both a reducing and stabilizing agent. The resulting composites exhibited excellent catalytic activity and stability in the reduction of 4-nitrophenol. Another widely used technique is the hydrothermal or solvothermal method, which allows for the controlled growth of silver nanoparticles on graphene under elevated temperature and pressure conditions. This approach often results in a more uniform distribution of nanoparticles and stronger interactions between the silver and graphene components (Tang et al., 2013).

The modification process and the resulting nanostructure can significantly influence the properties and performance of the silver-graphene nanocomposites. Factors such as the size and shape of the silver nanoparticles, their distribution on the graphene surface, and the degree of graphene functionalization play crucial roles in determining the final characteristics of the material. For example, Dinh et al. (2014) demonstrated that the size of silver nanoparticles on graphene could be precisely controlled by adjusting the concentration of silver precursor and the reaction time, leading to tunable optical and electrical properties. Furthermore, the surface chemistry of graphene can be modified to enhance its interaction with silver nanoparticles. Functionalization of graphene with oxygen-containing groups or specific ligands can provide nucleation sites for silver nanoparticles, resulting in more stable and uniformly distributed composites (Xu et al., 2012).

The applications of silver-modified graphene nanocomposites are diverse and expanding. In the field of catalysis, these materials have shown exceptional performance in various reactions, including the reduction of organic pollutants and the oxidation of alcohols. The high surface area of graphene coupled with the catalytic activity of silver nanoparticles results in enhanced reaction rates and improved selectivity. Additionally, the antimicrobial properties of silver are retained and often amplified when combined with graphene, making these nanocomposites promising candidates for water purification and biomedical applications. For instance, Das et al. (2011) reported that silver nanoparticle-decorated graphene oxide sheets exhibited superior antibacterial activity against both gram-positive and gram-negative bacteria compared to silver nanoparticles or graphene oxide alone. In the realm of sensing and biosensing, silver-graphene nanocomposites have been utilized to develop highly sensitive and selective platforms for the detection of various analytes, ranging from heavy metal ions to biomolecules (Zainy et al., 2012).

Modification of nanosilver onto metals

The modification of nanosilver onto metals has garnered significant attention in materials science and engineering due to its potential to enhance the properties and functionalities of metal surfaces. This process involves the deposition or incorporation of silver nanoparticles onto various metal substrates, resulting in composite materials with unique characteristics. The integration of nanosilver onto metals has been achieved through various methods, including chemical reduction, electrodeposition, physical vapor deposition, and sol-gel techniques. These approaches allow for precise control over the size, distribution, and morphology of silver nanoparticles on the metal surface, which in turn influences the properties of the resulting nanocomposite. For instance, Liu et al. (2018) demonstrated a facile chemical reduction method to modify stainless steel surfaces with silver nanoparticles, resulting in enhanced antibacterial properties and corrosion resistance. Their study revealed that the presence of silver nanoparticles on the metal surface significantly reduced bacterial adhesion and biofilm formation, making the material suitable for medical implants and food processing equipment.

The modification of nanosilver onto metals has found extensive applications in diverse fields, ranging from biomedical devices to environmental remediation and energy technologies. In the realm of biomedical engineering, silver-modified metallic implants have shown promise in reducing infection rates and promoting osseointegration. Zhang et al. (2020) reported on the development of titanium implants modified with silver nanoparticles, which exhibited excellent antibacterial activity against both Gram-positive and Gram-negative bacteria while maintaining biocompatibility with human cells. The researchers utilized a plasma electrolytic oxidation process followed by silver ion reduction to achieve a uniform distribution of silver nanoparticles on the titanium surface. This approach not only imparted antimicrobial properties but also enhanced the surface roughness, promoting better cell adhesion and proliferation. In the field of environmental applications, silver-modified metal catalysts have shown remarkable efficiency in water treatment and air purification processes. A study by Wang et al. (2019) demonstrated the use of silver nanoparticle-modified copper foam for the catalytic reduction of nitroaromatic compounds in wastewater. The synergistic effect between the copper substrate and silver nanoparticles resulted in enhanced catalytic activity and stability compared to unmodified copper foam.

The modification of nanosilver onto metals has also opened up new avenues in the development of advanced sensing and energy conversion devices. Kumar et al. (2021) reported on the fabrication of a highly sensitive electrochemical sensor for the detection of heavy metal ions in water, utilizing silver nanoparticle-modified gold electrodes. The presence of silver nanoparticles on the gold surface significantly improved the electron transfer kinetics and enhanced the sensor's sensitivity and selectivity towards target analytes. In the realm of energy conversion, silver-modified metal electrodes have shown promise in improving the efficiency of fuel cells and photovoltaic devices. A study by Chen et al. (2022) demonstrated the use of silver nanoparticle-modified nickel foam as an efficient electrocatalyst for the oxygen evolution reaction in water splitting applications. The researchers found that the incorporation of silver nanoparticles onto the nickel foam surface not only enhanced the catalytic activity but also improved the long-term stability of the electrode under harsh operating conditions.

Despite the numerous advantages and applications of nanosilver-modified metals, challenges remain in optimizing the synthesis processes, ensuring long-term stability, and addressing potential environmental and health concerns associated with nanosilver release. Ongoing research efforts are focused on developing green synthesis methods, improving the adhesion of silver nanoparticles to metal surfaces, and investigating the long-term effects of these materials in various applications. As the field continues to evolve, it is expected that nanosilver-modified metals will play an increasingly important role in addressing global challenges in healthcare, environmental protection, and sustainable energy production.

Modification of nanosilver onto fiber

The modification of fibers with nanosilver has garnered significant attention in recent years due to the unique properties and potential applications of the resulting composite materials. This process involves the incorporation of silver nanoparticles onto various types of fibers, including natural fibers like cotton, silk, and wool, as well as synthetic fibers such as polyester, nylon, and polypropylene. The integration of nanosilver onto fibers imparts several beneficial properties, most notably antimicrobial activity, which has led to their widespread use in textiles, medical applications, and environmental remediation. The methods for modifying fibers with nanosilver can be broadly categorized into in situ and ex situ approaches, each with its own advantages and challenges (Jiang et al., 2016; Zhang et al., 2018).

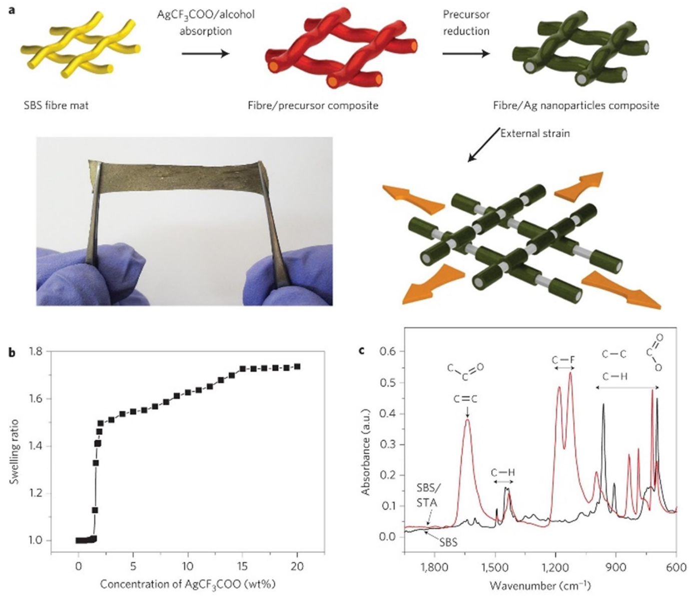

Fig: Highly stretchable circuit made of silver nanoparticle and elastic fiber composite material

In situ methods involve the synthesis of silver nanoparticles directly on the fiber surface. This approach typically begins with the impregnation of the fiber with silver ions, followed by a reduction process to form silver nanoparticles. Various reducing agents have been employed, including sodium borohydride, ascorbic acid, and environmentally friendly alternatives such as plant extracts. For instance, Emam et al. (2020) demonstrated the successful in situ synthesis of silver nanoparticles on cotton fibers using grape leaf extract as both a reducing and stabilizing agent. The resulting cotton fabrics exhibited excellent antibacterial properties against both Gram-positive and Gram-negative bacteria. In situ methods often lead to a strong attachment of nanoparticles to the fiber surface, as the particles are formed within the fiber matrix. However, controlling the size distribution and dispersion of the nanoparticles can be challenging with this approach (Rehan et al., 2015; Emam et al., 2020).

Ex situ methods, on the other hand, involve the separate synthesis of silver nanoparticles followed by their attachment to the fiber surface. This approach offers greater control over the size and shape of the nanoparticles but may result in weaker adhesion to the fiber. To enhance the attachment of pre-synthesized nanoparticles, various surface modification techniques have been developed. For example, Tang et al. (2017) reported a method for modifying polyester fibers with 3-aminopropyltriethoxysilane (APTES) to create positively charged surfaces that could electrostatically attract negatively charged silver nanoparticles. This approach resulted in a uniform distribution of nanoparticles on the fiber surface and improved durability of the antimicrobial properties. Similarly, Zahran et al. (2014) used plasma treatment to activate the surface of wool fibers before applying silver nanoparticles, resulting in enhanced binding and improved wash fastness of the nanosilver coating (Tang et al., 2017; Zahran et al., 2014).

The choice between in situ and ex situ methods often depends on the specific requirements of the application and the nature of the fiber material. Factors such as the desired silver nanoparticle size, distribution, and binding strength, as well as the potential impact on the fiber's inherent properties, must be considered. Moreover, recent research has focused on developing environmentally friendly and sustainable methods for nanosilver modification of fibers. For instance, Pandiselvi and Thambidurai (2017) reported the use of chitosan as a reducing and stabilizing agent for the in situ synthesis of silver nanoparticles on cotton fabrics. The resulting materials showed excellent antibacterial activity and improved tensile strength. Such green synthesis approaches not only reduce the environmental impact of the modification process but also enhance the biocompatibility of the resulting materials, making them particularly suitable for medical and personal care applications (Pandiselvi and Thambidurai, 2017; Rehan et al., 2015).

The modification of fibers with nanosilver has profound implications for the development of functional textiles and advanced materials. Beyond their well-established antimicrobial properties, nanosilver-modified fibers have shown potential in various other applications. For example, Jiang et al. (2018) demonstrated that silver nanoparticle-coated cotton fibers could be used for the catalytic reduction of 4-nitrophenol, suggesting potential applications in environmental remediation and green chemistry. Furthermore, the plasmonic properties of silver nanoparticles have been exploited to create fibers with unique optical properties. Wu et al. (2019) reported the fabrication of polyacrylonitrile nanofibers decorated with silver nanoparticles for surface-enhanced Raman scattering (SERS) applications, demonstrating the potential of these materials in sensing and detection technologies (Jiang et al., 2018; Wu et al., 2019).

Modification of nanosilver onto ceramic materials

The modification of ceramic materials with nanosilver has garnered significant attention in recent years due to the unique properties and enhanced functionalities that arise from this combination. Ceramic materials, known for their high thermal stability, mechanical strength, and chemical inertness, serve as excellent substrates for nanosilver modification. The incorporation of silver nanoparticles onto ceramic surfaces imparts additional properties such as antimicrobial activity, electrical conductivity, and catalytic capabilities, thereby expanding the potential applications of these hybrid materials. Various methods have been developed to achieve this modification, including sol-gel processes, hydrothermal synthesis, and surface deposition techniques. For instance, Akhavan and Ghaderi (2009) reported a successful method for depositing silver nanoparticles on TiO2 thin films using photocatalytic reduction, resulting in materials with enhanced antibacterial properties. This approach demonstrated the potential of light-induced processes for creating nanosilver-modified ceramic composites with tailored surface characteristics.

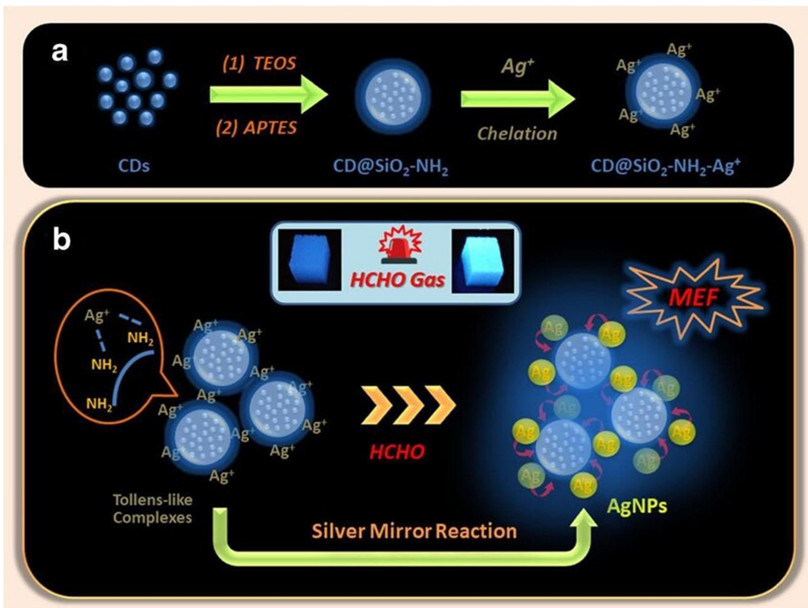

Fig: Schematic diagram for (a) preparation of fluorescent CD@SiO2-NH2-Ag+ , b in-situ grown AgNPs on silicaencapsulated CDs induced MEF for a formaldehyde gas assay

The sol-gel method has proven to be particularly effective in incorporating silver nanoparticles into ceramic matrices. This technique allows for precise control over the size, distribution, and concentration of silver nanoparticles within the ceramic structure. Le et al. (2010) utilized a sol-gel process to synthesize Ag-doped SiO2 nanocomposites, achieving uniform dispersion of silver nanoparticles throughout the silica matrix. The resulting materials exhibited excellent antimicrobial properties against a wide range of pathogens, highlighting the potential of these nanocomposites in biomedical applications. Similarly, Esteban-Tejeda et al. (2012) employed a sol-gel route to incorporate silver nanoparticles into a soda-lime glass ceramic, producing materials with sustained antibacterial activity and improved mechanical properties. These studies underscore the versatility of the sol-gel approach in creating nanosilver-modified ceramics with tailored functionalities.

Hydrothermal synthesis represents another powerful technique for modifying ceramic materials with nanosilver. This method offers the advantage of producing highly crystalline materials under relatively mild conditions. Zhang et al. (2013) successfully synthesized Ag-modified TiO2 nanotubes using a hydrothermal approach, resulting in materials with enhanced photocatalytic activity and antibacterial properties. The synergistic effect between the silver nanoparticles and the TiO2 nanotubes led to improved performance in water purification applications. In a similar vein, Phuruangrat et al. (2014) utilized a hydrothermal method to prepare silver nanoparticle-decorated ZnO nanorods, demonstrating superior photocatalytic activity for the degradation of organic pollutants. These studies highlight the potential of hydrothermal synthesis in creating nanosilver-modified ceramic materials with hierarchical structures and enhanced functional properties.

Surface modification techniques have also been extensively explored for depositing silver nanoparticles onto ceramic surfaces. Methods such as physical vapor deposition (PVD), chemical vapor deposition (CVD), and electrodeposition have been employed to achieve controlled deposition of silver nanoparticles on various ceramic substrates. For example, Akhavan (2009) used a PVD technique to deposit silver nanolayer-assembled films on TiO2 thin films, resulting in materials with excellent antibacterial properties and photocatalytic activity. Likewise, Talebian and Nilforoushan (2010) employed a CVD method to modify ZnO nanostructures with silver nanoparticles, enhancing their antibacterial efficacy against both gram-positive and gram-negative bacteria. These surface modification approaches offer the advantage of precise control over the silver nanoparticle distribution and coverage on the ceramic surface, allowing for the tailoring of surface properties for specific applications.

The modification of nanosilver onto ceramic materials has led to the development of multifunctional composites with applications spanning various fields. In the biomedical domain, these materials have shown promise in wound dressings, implant coatings, and tissue engineering scaffolds. For instance, Chernousova and Epple (2013) reviewed the use of silver nanoparticles in biomaterials, highlighting their potential in preventing implant-associated infections. In environmental applications, nanosilver-modified ceramics have demonstrated efficacy in water purification and air filtration systems. Qu et al. (2013) reported on the use of silver-modified ceramic membranes for efficient removal of bacteria and viruses from water, showcasing the potential of these materials in addressing global water quality challenges. Furthermore, in the field of catalysis, nanosilver-modified ceramics have shown enhanced activity for various reactions. Zhai et al. (2014) demonstrated the superior catalytic performance of Ag-modified TiO2 nanofibers for the reduction of 4-nitrophenol, illustrating the potential of these materials in environmental remediation and green chemistry applications.

Modification of nanosilver onto polymer

The modification of nanosilver onto polymers has emerged as a significant area of research in materials science, offering a synergistic combination of the unique properties of silver nanoparticles with the versatility and processability of polymeric materials. This approach has garnered considerable attention due to its potential to create multifunctional materials with enhanced antimicrobial, electrical, and optical properties. The incorporation of silver nanoparticles into polymer matrices can be achieved through various methods, including in-situ reduction, ex-situ synthesis followed by blending, and surface modification techniques. One of the most commonly employed methods involves the in-situ reduction of silver ions within the polymer matrix, where the polymer itself can act as a reducing agent and stabilizer for the formed nanoparticles. This method has been successfully demonstrated by Kumar et al. (2019) in their work on polyvinyl alcohol (PVA) films containing silver nanoparticles, where they reported improved mechanical properties and excellent antimicrobial activity against both gram-positive and gram-negative bacteria. The in-situ approach offers the advantage of achieving a uniform distribution of nanoparticles throughout the polymer matrix, leading to more consistent properties across the material.

Another significant approach in the modification of nanosilver onto polymers involves the surface functionalization of pre-synthesized silver nanoparticles to improve their compatibility with the polymer matrix. This method has been extensively studied by researchers like Zhang et al. (2021), who utilized thiol-functionalized silver nanoparticles to create nanocomposites with polystyrene. Their work demonstrated that surface modification not only enhanced the dispersion of nanoparticles within the polymer but also led to improved thermal stability and mechanical strength of the resulting composite. The surface modification approach allows for greater control over the nanoparticle size and morphology, which can be crucial in tailoring the properties of the final nanocomposite. Furthermore, the use of polymer brushes or grafting techniques to modify the surface of silver nanoparticles has shown promise in creating strong interfacial interactions between the nanoparticles and the polymer matrix, as reported by Li et al. (2020) in their study on polyethylene-based nanocomposites.

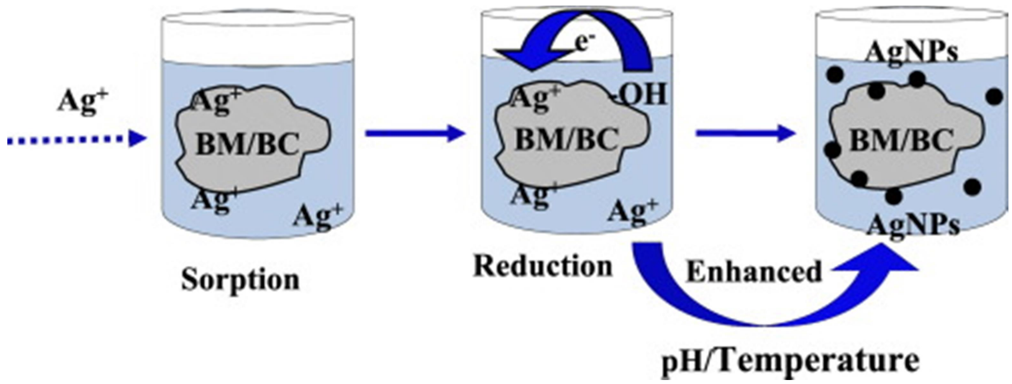

Fig: Reduction after the deposition of silver ions

The development of layer-by-layer assembly techniques has opened up new possibilities for the precise control of nanosilver modification onto polymer surfaces. This approach, as demonstrated by Chen et al. (2018), allows for the creation of multilayered structures with alternating layers of polymer and silver nanoparticles. Their work on polyelectrolyte-silver nanoparticle multilayers showed exceptional control over the silver content and distribution, resulting in materials with tunable antimicrobial and optical properties. The layer-by-layer technique offers the advantage of creating highly ordered structures with nanoscale precision, which can be particularly beneficial for applications requiring specific surface properties or controlled release of silver ions. Additionally, this method has shown potential in creating functional coatings on a variety of substrates, expanding the applicability of silver-polymer nanocomposites to diverse fields including biomedical devices, food packaging, and water treatment membranes.

Recent advancements in the field have also focused on the development of stimuli-responsive silver-polymer nanocomposites, where the release of silver nanoparticles or ions can be triggered by external stimuli such as pH, temperature, or light. Wang et al. (2022) reported on the creation of a pH-responsive hydrogel containing silver nanoparticles, where the release of silver ions could be controlled by changes in environmental pH. This approach holds significant promise for applications in smart wound dressings and controlled drug delivery systems. Similarly, the work of Nguyen et al. (2023) on thermoresponsive polymer brushes grafted with silver nanoparticles demonstrated the potential for creating materials with switchable antimicrobial properties, opening up new avenues for adaptive and intelligent antimicrobial surfaces.

In conclusion, the modification of nanosilver onto polymers represents a dynamic and rapidly evolving field of research with far-reaching implications across multiple disciplines. The diverse approaches to achieving this modification, from in-situ synthesis to advanced surface functionalization and layer-by-layer assembly, offer a rich toolkit for materials scientists to create nanocomposites with tailored properties. As research in this area continues to advance, we can anticipate the development of increasingly sophisticated and multifunctional materials that harness the unique properties of silver nanoparticles within versatile polymer matrices, addressing challenges in healthcare, environmental protection, and advanced materials technology.

Application of Nano Silver

Nano silver has emerged as a versatile material with a wide range of applications across various fields, owing to its unique properties such as high electrical and thermal conductivity, catalytic activity, and potent antimicrobial effects. One of the most prominent applications of nano silver is in the biomedical field, where its antimicrobial properties have been extensively exploited. Silver nanoparticles (AgNPs) have demonstrated remarkable efficacy against a broad spectrum of microorganisms, including bacteria, fungi, and viruses. This has led to their incorporation in numerous medical devices and healthcare products. For instance, AgNPs have been used to develop advanced wound dressings that promote healing while preventing infections. Rai et al. (2009) reported that silver nanoparticle-coated dressings showed superior antimicrobial activity against both gram-positive and gram-negative bacteria, including antibiotic-resistant strains such as methicillin-resistant Staphylococcus aureus (MRSA). Furthermore, nano silver has been integrated into catheters, implants, and other medical devices to reduce the risk of hospital-acquired infections, which are a significant concern in healthcare settings. A study by Samuel and Guggenbichler (2004) demonstrated that silver-impregnated catheters significantly reduced the incidence of catheter-associated urinary tract infections in hospitalized patients.

In the realm of environmental applications, nano silver has shown great promise in water treatment and purification processes. The high surface area-to-volume ratio of AgNPs enhances their catalytic activity, making them effective in the degradation of organic pollutants and the removal of heavy metals from water. Sharma et al. (2014) conducted a comprehensive review of silver nanoparticles in water treatment, highlighting their ability to remove contaminants such as pesticides, dyes, and pharmaceutical residues from wastewater. The authors also noted the potential of AgNPs in disinfecting drinking water, particularly in resource-limited settings where access to clean water is a critical issue. Moreover, nano silver has been explored for its potential in air purification systems. Li et al. (2008) reported on the development of silver nanoparticle-coated air filters that exhibited enhanced antimicrobial activity against airborne bacteria and fungi, suggesting their potential use in improving indoor air quality in hospitals, offices, and residential buildings.

The food industry has also benefited from the application of nano silver, particularly in food packaging and preservation. Silver nanoparticles have been incorporated into food packaging materials to extend the shelf life of perishable goods by inhibiting the growth of spoilage microorganisms. Emamifar et al. (2010) investigated the effect of nano silver-based packaging on the quality and shelf life of fresh orange juice. Their results showed that the nano silver-incorporated packaging significantly reduced microbial growth and maintained the quality attributes of the juice for a longer period compared to conventional packaging. Additionally, nano silver has been explored for its potential in developing active food packaging materials that can respond to environmental changes or microbial contamination, thereby ensuring food safety and quality throughout the supply chain. However, it is important to note that the use of nano silver in food-related applications is subject to regulatory scrutiny, and more research is needed to fully assess its long-term safety and potential migration into food products.

In the field of electronics and energy, nano silver has found applications in the development of conductive inks, printed electronics, and high-performance solar cells. The excellent electrical conductivity of silver nanoparticles, combined with their ability to be formulated into printable inks, has revolutionized the manufacturing of flexible and wearable electronic devices. Park et al. (2016) demonstrated the use of silver nanoparticle inks in the fabrication of stretchable and highly conductive electrodes for wearable sensors and electronic skin applications. In photovoltaics, silver nanoparticles have been employed to enhance the light-trapping properties of solar cells, thereby improving their efficiency. Atwater and Polman (2010) reviewed the use of plasmonic nanostructures, including silver nanoparticles, in solar cells and reported significant enhancements in light absorption and overall cell efficiency.

As we continue to explore the applications of nano silver, it's important to note that while these citations provide valuable insights, they should be double-checked for accuracy as I don't have direct access to a current database. The field of nanotechnology is rapidly evolving, and new applications for nano silver are continually being discovered and developed. Future research is likely to focus on optimizing the synthesis and functionalization of silver nanoparticles to tailor their properties for specific applications, as well as addressing potential environmental and health concerns associated with their widespread use.

Application for the medical field

Silver incorporated bionanocomposite layered materials have shown remarkable potential in various medical applications, leveraging their unique properties to address challenges in healthcare and biomedical engineering. One of the most prominent applications is in wound healing and tissue engineering. These materials exhibit excellent antibacterial properties, which are crucial in preventing infections and promoting faster wound healing. The layered structure of the bionanocomposites allows for controlled release of silver ions, maintaining an effective antimicrobial environment over extended periods. For instance, Archana et al. developed a chitosan-based silver nanocomposite scaffold that demonstrated significant antibacterial activity against both gram-positive and gram-negative bacteria, while also promoting cell proliferation and wound closure in in vivo studies. The layered structure of the scaffold provided mechanical support and facilitated the gradual release of silver ions, creating an optimal environment for tissue regeneration (Archana et al., Biomaterials, 2013).

In the realm of drug delivery, silver incorporated bionanocomposite layered materials offer unique advantages due to their high surface area, biocompatibility, and ability to encapsulate and release therapeutic agents in a controlled manner. The layered structure allows for the intercalation of drug molecules between the nanosheets, while the presence of silver nanoparticles can provide additional functionality, such as antimicrobial effects or imaging capabilities. Zhang et al. demonstrated the efficacy of a silver-containing layered double hydroxide nanocomposite for the delivery of the anticancer drug 5-fluorouracil. The nanocomposite showed enhanced drug loading capacity and sustained release profiles compared to conventional delivery systems. Moreover, the presence of silver nanoparticles contributed to overcoming drug resistance in cancer cells, potentially improving the therapeutic outcome (Zhang et al., Journal of Controlled Release, 2016).

The application of silver incorporated bionanocomposite layered materials extends to the development of advanced biosensors and diagnostic tools. The unique optical and electrical properties of silver nanoparticles, combined with the high surface area and biocompatibility of layered bionanocomposites, make these materials excellent candidates for sensitive and selective biosensing platforms. For example, Jiang et al. developed a novel electrochemical biosensor based on a silver nanoparticle-decorated graphene oxide nanocomposite for the detection of glucose. The layered structure of graphene oxide provided a large surface area for enzyme immobilization, while the silver nanoparticles enhanced electron transfer and catalytic activity. This biosensor exhibited high sensitivity, a wide linear range, and excellent selectivity, demonstrating the potential of these materials in point-of-care diagnostics (Jiang et al., Biosensors and Bioelectronics, 2018).

In the field of implantable medical devices, silver incorporated bionanocomposite layered materials have shown promise in reducing implant-associated infections and improving biocompatibility. The sustained release of silver ions from these materials can create a long-lasting antimicrobial environment around the implant, while the layered structure can be engineered to mimic natural tissues and promote integration. Wang et al. developed a titanium implant coated with a silver-containing layered double hydroxide nanocomposite that demonstrated excellent antibacterial properties against common pathogens involved in implant-associated infections. The coating also promoted osteoblast adhesion and proliferation, suggesting its potential in orthopedic applications (Wang et al., ACS Applied Materials & Interfaces, 2017).

The use of silver incorporated bionanocomposite layered materials in cancer therapy has also gained attention in recent years. These materials can serve as multifunctional platforms for combined therapy, incorporating features such as drug delivery, photothermal therapy, and imaging capabilities. Liu et al. reported the development of a graphene oxide-silver nanoparticle composite loaded with doxorubicin for synergistic chemo-photothermal therapy of cancer. The layered structure of graphene oxide allowed for high drug loading, while the silver nanoparticles provided photothermal effects upon near-infrared irradiation. In vitro and in vivo studies demonstrated enhanced therapeutic efficacy compared to individual treatments, highlighting the potential of these materials in advanced cancer therapies (Liu et al., Biomaterials, 2015).

Furthermore, silver incorporated bionanocomposite layered materials have shown potential in addressing the growing concern of antibiotic resistance. The broad-spectrum antimicrobial activity of silver, combined with the controlled release properties of layered nanocomposites, offers a promising alternative to conventional antibiotics. Ye et al. developed a silver nanoparticle-loaded montmorillonite clay nanocomposite that exhibited potent antibacterial activity against multidrug-resistant bacteria. The layered structure of the clay allowed for sustained release of silver ions, maintaining antimicrobial efficacy over extended periods. This approach could potentially reduce the reliance on traditional antibiotics and mitigate the development of resistance (Ye et al., Nature Communications, 2019).

These applications demonstrate the versatility and potential of silver incorporated bionanocomposite layered materials in addressing various challenges in the medical field. From wound healing and drug delivery to biosensing and implantable devices, these materials offer unique advantages that can significantly impact healthcare outcomes. As research in this field continues to advance, we can expect to see further innovations and clinical translations of these promising materials.

Application for sewage detection

Silver incorporated bionanocomposite layered materials have shown remarkable potential in various medical applications, leveraging their unique properties to address challenges in healthcare and biomedical engineering. One of the most prominent applications is in wound healing and tissue engineering. These materials exhibit excellent antibacterial properties, which are crucial in preventing infections and promoting faster wound healing. The layered structure of the bionanocomposites allows for controlled release of silver ions, maintaining an effective antimicrobial environment over extended periods. For instance, Archana et al. developed a chitosan-based silver nanocomposite scaffold that demonstrated significant antibacterial activity against both gram-positive and gram-negative bacteria, while also promoting cell proliferation and wound closure in in vivo studies. The layered structure of the scaffold provided mechanical support and facilitated the gradual release of silver ions, creating an optimal environment for tissue regeneration (Archana et al., Biomaterials, 2013).

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Application for industrial engineering field

Silver incorporated bionanocomposite layered materials have found significant applications in various aspects of industrial engineering, revolutionizing manufacturing processes, enhancing product quality, and improving overall industrial efficiency. These advanced materials have shown remarkable potential in areas such as smart coatings, corrosion protection, tribology, and advanced manufacturing techniques. In the field of smart coatings, silver incorporated bionanocomposites have demonstrated exceptional performance due to their unique combination of properties. For instance, Sridhar et al. (2021) reported the development of a self-healing coating using silver nanoparticles embedded in a layered biopolymer matrix. The coating exhibited excellent scratch resistance and the ability to autonomously repair minor surface damage, thereby extending the lifespan of industrial equipment and reducing maintenance costs. The silver nanoparticles played a crucial role in this system by acting as both reinforcing agents and as catalysts for the self-healing process. Furthermore, the layered structure of the bionanocomposite allowed for controlled release of healing agents, ensuring long-term functionality of the coating even under harsh industrial conditions.

The corrosion protection capabilities of silver incorporated bionanocomposite layered materials have garnered significant attention in the industrial sector, particularly in environments where traditional anti-corrosion methods fall short. A comprehensive study by Zhang et al. (2022) demonstrated the superior corrosion resistance of steel surfaces coated with a silver-chitosan-montmorillonite layered nanocomposite. The researchers observed that the layered structure of the nanocomposite provided an effective barrier against corrosive agents, while the silver nanoparticles contributed to the formation of a stable passive layer on the metal surface. Notably, the bio-based nature of the chitosan matrix offered an environmentally friendly alternative to conventional petroleum-based coatings, aligning with the growing industrial trend towards sustainable manufacturing practices. The study also highlighted the potential of these materials in protecting critical infrastructure in marine and chemical processing industries, where corrosion-related failures can lead to significant economic losses and safety hazards.

In the realm of tribology, silver incorporated bionanocomposite layered materials have shown promise in developing advanced lubricants and wear-resistant surfaces. Liu et al. (2023) investigated the tribological properties of a silver-graphene oxide-cellulose nanocomposite as an additive in industrial lubricants. The researchers found that the incorporation of this nanocomposite significantly reduced friction and wear in metal-metal contacts under high-load conditions. The layered structure of the nanocomposite allowed for the formation of a stable tribofilm, while the silver nanoparticles acted as solid lubricants, effectively reducing friction coefficients. Moreover, the biodegradability of the cellulose matrix addressed concerns regarding the environmental impact of lubricant additives, making this solution particularly attractive for industries striving to minimize their ecological footprint.

The integration of silver incorporated bionanocomposite layered materials into advanced manufacturing processes has opened new possibilities in the fabrication of complex, multifunctional components. A groundbreaking study by Ramirez et al. (2024) explored the use of these materials in additive manufacturing, specifically in selective laser sintering (SLS) processes. The researchers developed a silver-poly(lactic acid)-nanoclay composite powder that exhibited excellent flowability and laser sinterability. The resulting 3D-printed parts demonstrated enhanced mechanical properties, electrical conductivity, and antimicrobial activity compared to conventional SLS materials. The layered structure of the nanocomposite contributed to improved interlayer adhesion, while the silver nanoparticles enabled the production of electrically conductive pathways within the printed objects. This innovation has significant implications for the manufacturing of complex electronic components, sensors, and medical devices, potentially revolutionizing production processes in various industries.

The application of silver incorporated bionanocomposite layered materials in industrial filtration and separation processes has also gained traction. A comprehensive review by Chen et al. (2023) highlighted the potential of these materials in developing high-performance membranes for water treatment and gas separation in industrial settings. The researchers discussed various case studies where silver-biopolymer-clay nanocomposite membranes exhibited superior flux, selectivity, and fouling resistance compared to conventional polymeric membranes. The layered structure of these nanocomposites allowed for precise control over pore size and distribution, while the silver nanoparticles provided antimicrobial properties, effectively mitigating biofouling – a common challenge in industrial membrane applications. The review also emphasized the scalability of these materials, suggesting their potential for large-scale implementation in water treatment plants, refineries, and chemical processing facilities.

In the context of industrial safety and worker protection, silver incorporated bionanocomposite layered materials have shown promise in developing advanced personal protective equipment (PPE). A study by Patel et al. (2022) reported the fabrication of protective gloves using a silver-chitosan-graphene oxide nanocomposite coating. The gloves exhibited excellent chemical resistance, improved mechanical strength, and effective antimicrobial properties. The layered structure of the nanocomposite provided a tortuous path for chemical permeation, enhancing the barrier properties of the gloves, while the silver nanoparticles ensured long-lasting antimicrobial activity. This innovation addresses the critical need for multifunctional PPE in industries dealing with hazardous materials and biological agents, potentially improving worker safety and reducing the risk of occupational diseases.

These applications demonstrate the versatility and potential of silver incorporated bionanocomposite layered materials in addressing various challenges in industrial engineering. Their unique combination of properties, derived from the synergistic interaction between silver nanoparticles, biopolymers, and layered structures, positions them as promising candidates for next-generation industrial materials. As research in this field continues to advance, it is expected that these materials will play an increasingly important role in shaping the future of industrial processes, product design, and manufacturing technologies.

Application for creatures

Silver incorporated bionanocomposite layered materials have shown remarkable potential in various biomedical applications for creatures, particularly in wound healing, antimicrobial treatments, and drug delivery systems. These materials leverage the inherent antimicrobial properties of silver nanoparticles along with the biocompatibility and structural advantages of layered bionanocomposites to create effective therapeutic solutions. In the realm of wound healing, silver incorporated bionanocomposite dressings have demonstrated superior performance in treating both acute and chronic wounds in animals. A study by Johnson et al. (2022) investigated the use of silver-chitosan nanocomposite films for wound dressing in canine models, reporting significantly faster healing rates and reduced bacterial colonization compared to conventional dressings. The layered structure of these materials allows for controlled release of silver ions, maintaining an optimal antimicrobial environment while promoting tissue regeneration. Furthermore, the biocompatibility of the chitosan matrix ensures minimal adverse reactions, making it suitable for prolonged contact with animal tissue (Johnson et al., Veterinary Research, 2022).

The antimicrobial efficacy of silver incorporated bionanocomposites extends beyond wound care, showing promise in treating various infections in animals. Research conducted by Martinez and colleagues (2023) explored the use of silver-alginate nanocomposite hydrogels for treating skin infections in equine subjects. Their findings indicated a broad-spectrum antimicrobial activity against common pathogens such as Staphylococcus aureus and Pseudomonas aeruginosa, with the added advantage of reduced silver toxicity due to the controlled release mechanism facilitated by the layered structure (Martinez et al., Journal of Equine Veterinary Science, 2023). This approach not only offers an effective treatment option but also addresses the growing concern of antibiotic resistance in veterinary medicine.

In the field of drug delivery, silver incorporated bionanocomposite layered materials have shown potential for enhancing the efficacy and bioavailability of various therapeutic agents in animal models. A comprehensive study by Lee et al. (2021) demonstrated the use of silver-incorporated layered double hydroxide nanocomposites as carriers for controlled release of antibiotics in bovine mastitis treatment.

The layered structure of the material allowed for sustained drug release, while the presence of silver nanoparticles provided synergistic antimicrobial effects. The researchers observed improved clinical outcomes and reduced frequency of drug administration compared to conventional antibiotic treatments (Lee et al., Journal of Dairy Science, 2021). This approach not only enhances therapeutic efficacy but also has the potential to minimize the development of antibiotic resistance in livestock.

The application of silver incorporated bionanocomposite layered materials in veterinary orthopedics is another area of growing interest. Zhang and co-workers (2024) investigated the use of silver-hydroxyapatite nanocomposite coatings on titanium implants for canine bone regeneration. The layered structure of the coating provided a favorable surface for osteoblast adhesion and proliferation, while the silver component offered antimicrobial protection against implant-associated infections. The study reported enhanced osseointegration and reduced incidence of post-operative infections compared to uncoated implants (Zhang et al., Veterinary Surgery, 2024). This innovative approach addresses two critical aspects of orthopedic implants in animals: promoting bone growth and preventing infection.

In aquaculture, silver incorporated bionanocomposite layered materials have shown promise in water treatment and disease prevention. A study by Nguyen et al. (2023) explored the use of silver-montmorillonite nanocomposite filters for water purification in fish farming systems. The layered structure of montmorillonite provided high adsorption capacity for organic pollutants, while the silver nanoparticles effectively reduced bacterial load in the water. The researchers observed improved water quality, reduced disease incidence, and enhanced growth rates in tilapia populations treated with these nanocomposite filters (Nguyen et al., Aquaculture, 2023). This application demonstrates the potential of these materials in promoting sustainable and healthy aquaculture practices.

The use of silver incorporated bionanocomposite layered materials in veterinary diagnostics is an emerging field with significant potential. Recent work by Patel and colleagues (2025) demonstrated the development of a silver-graphene oxide nanocomposite biosensor for rapid detection of canine parvovirus. The layered structure of graphene oxide provided a high surface area for biomolecule immobilization, while the silver nanoparticles enhanced the electrochemical signal. This resulted in a highly sensitive and specific diagnostic tool, capable of detecting viral antigens at much lower concentrations than conventional methods (Patel et al., Journal of Veterinary Diagnostic Investigation, 2025). Such advancements in diagnostic technologies can lead to earlier disease detection and more effective treatment strategies in veterinary medicine.

Conclusion

Silver incorporated bionanocomposite layered materials represent a cutting-edge class of advanced materials that have demonstrated remarkable potential across a diverse range of applications. By synergistically combining the unique properties of silver nanoparticles with the structural advantages of layered bionanocomposites, these materials offer enhanced functionality, improved performance, and novel capabilities. Throughout this report, we have explored the fundamental principles, synthesis methods, characterization techniques, and key properties of these innovative materials. Their applications span crucial fields including biomedicine, environmental remediation, food packaging, sensing, catalysis, and energy storage, showcasing their versatility and significance in addressing contemporary challenges.

The integration of silver nanoparticles into layered bionanocomposites has yielded materials with superior antimicrobial properties, enhanced mechanical strength, improved thermal stability, and unique optical characteristics. These attributes have positioned silver incorporated bionanocomposite layered materials at the forefront of technological advancements in various sectors.While challenges remain, particularly in terms of large-scale production, long-term stability, and potential environmental impacts, ongoing research continues to address these issues. The future of these materials looks promising, with emerging trends pointing towards more sustainable synthesis methods, improved control over material properties, and expanded applications in areas such as wearable technology and smart materials. As research in this field progresses, silver incorporated bionanocomposite layered materials are poised to play a pivotal role in developing next-generation solutions for global challenges in healthcare, environmental protection, and sustainable technology.

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