

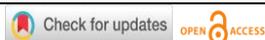
# A Comprehensive Review on Synthesis, Properties, and Applications of CdS/Ag-Doped Polyvinyl Alcohol (PVA) Nanocomposites

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## ABSTRACT

**Objective:** Nanoparticle addition in the polymer matrix is a recent development in the materials science whereby composite materials are produced with special properties that are superior to that of the material used. Special attention has been given to nanocomposites made on polyvinyl alcohol (PVA) which involve nanoparticles of silver (Ag) and cadmium sulphide (CdS). The review will entail a critical review of the recent innovations in the synthesis procedures of PVA nanocomposites with CdS and Ag doping. **Method :** The techniques employed in determining the significant changes in mechanical, optical, electrical and structural characteristics of the components are SEM, FTIR, XRD and UV-VIS spectroscopy. **Results :** A substrate is a great polymer that is soluble in water, biodegradable and exceedingly flexible: PVA has a large density of functional hydroxyl groups that stabilize the nanoparticles, in addition, it has a good chemical stability as well as forming a film. CdS is a top quality tunable bandgap II- VI semiconductor that possesses excellent optical and photocatalytic characteristics. Electrical conductivity and antimicrobial action of silver nanoparticles (SPs) in the form of plasmonics are specifically impressive. The Ag and CdS in a PVA matrix is a multi-purpose nanocomposite with improved and variousiated functions. Besides, the review also takes a closer look at the growing uses of these nanocomposites in other industrial fields such as the flexible optoelectronics (e.g. 3). H. photodetectors, antimicrobial coats, radiation shielding, photocatalytic de-pollutionants, light-emitting diodes based on LED. Lastly, an argument is made on the present challenges and opportunities in the development and implementation of these innovative functional materials. **Novelty :** The Ag and CdS in a PVA matrix is a multi-purpose nanocomposite with improved and variousiated functions.

## INTRODUCTION

The polymer nanocomposites have grown exponentially in the past 2 decades due to the demands of lightweight and flexible as well as versatile materials. Close addition of the nanoscale (0D, 1D and 2D) fillers can significantly enhance the physical and chemical characteristics of the polymer host resulting in far broader uses than those achievable by traditional materials [1]. One such promising polymer matrix is polyvinyl alcohol (PVA) due to its amazing capacity of creating a film, its degree of hydrophilicity, chemical resistance, biodegradability and its biocompatibility. It has a big hydroxyl (-OH) backbone, which serves as an active site to nucleate and stabilise various forms of nanoparticles and functionalise these nanoparticles [2]. Cadmium sulphide (CdS) is a direct-gap semiconductor (~2.42 eV) with a high absorption of visible light and electron-hole pairs are easily generated. Owing to these properties, it is a fundamental constituent of solar cells, photodetectors and photocatalysts [3]. Likewise, silver nanoparticles (Ag NPs) are considered to be one of the most researched metallic nanoparticles because of

their specific surface plasmon resonance (SPR) in the visible spectrum that strengthens local electromagnetic fields. They are highly biocidal, conductive to electricity and thermal, and hence they are highly applicable in biomedical, electronic, and sensing applications [4]. The principle of formation of a ternary system, in which there is synergistic interaction, is the one that is applied with the co-administration of the PVA with nanoparticles of CdS and Ag. The polymer skeleton helps to avoid agglomeration of nanoparticles by acting as a stabilising and dispersing medium, but also provides mechanical strength and flexibility. Nanoparticles of metal and semiconductor are then used to give functionalities to an otherwise passive polymer. Potential interactions which could significantly enhance the separation of charges and the overall functionality of optoelectronic and photocatalytic applications include plasma-exciton coupling, charge transfer between CdS and Ag and the creation of Schottky barriers at the interface between semiconductors and metals [5]. Moreover, photocatalytic activity of CdS with the natural antimicrobial effect of Ag can be used to generate highly effective self-sterilising coating. This review is aimed at presenting an overview of the latest studies on CdS and Ag-doped PVA nanocomposites. It will consider the different synthesis routes, the characterisation techniques applied to study their properties and the wide application that they permit. The article can be of value to scholars in this multidisciplinary field where analysing the future trends and providing aggregated information in tabular form are useful.

## RESEARCH METHOD

### Synthesis and Fabrication Techniques

The synthesis process has a significant impact on the characteristics of CdS/Ag-PVA nanocomposites since it determines the size, distribution, and shape of the nanoparticles inside the polymer matrix. The methods can be broadly divided into two categories: *ex-situ*, which blends pre-formed nanoparticles with the polymer, and *in-situ*, which synthesizes nanoparticles within the polymer solution. For stronger interfacial adhesion and a more uniform distribution, *in-situ* techniques are typically recommended.

#### A. In-situ Chemical Reduction and Precipitation

The most popular technique for creating these nanocomposites is this one. PVA powder is usually dissolved in deionized water while being heated and stirred to create a clear, viscous solution. In order to incorporate Ag, a silver precursor (e. G. The PVA solution is supplemented with AgNO<sub>3</sub>. Although additional reducing agents, such as NaBH<sub>4</sub> or hydrazine hydrate, are occasionally used to control the reduction rate and particle size, PVA's hydroxyl groups frequently serve as both a reducing and a stabilizing/capping agent [6]. Cadmium precursor for CdS incorporation (e.g. G. CdCl<sub>2</sub>, Cd(NO<sub>3</sub>)<sub>2</sub>), and a source of sulfur (e.g. G. thiourea, Na<sub>2</sub>S) are added one after the other. Cadmium ions and sulfide ions combine to generate CdS nanoparticles, which then nucleate inside PVA chains. The final nanocomposite structure may be impacted by the order of addition (Ag first, followed by CdS, or vice versa), possibly resulting in core-

shell or mixed configurations. In order to create flexible nanocomposite films, the solution must be cast into Petri dishes and allowed to dry either at room temperature or in an oven [7].

### B. Sol-Gel Method

Sol-gel process provides an outstanding compositional and structural control at the molecular scale. In this method, the precursors are hydrolyzed and condensed to form a colloidal suspension (sol), which is allowed to solidify in the polymer framework to a forming network (gel). To form a CdS sol-gel network, e.g. cadmium precursor may be added to the PVA solution followed by the addition of the sulfur source. Ag NPs could also be fabricated by decreasing the quantity of silver ions introduced either simultaneously or subsequently. The result of this method may be a fine and uniform dispersion of nanoparticles [8].

### B. Microwave-Assisted Synthesis

Microwave irradiation is also a quick, effective, and energy-efficient technique of manufacturing nanoparticles. The even heating of the microwave leads to instant nucleation and accelerated growth of nanoparticles and this leads to a fine size distribution. In this method, a short duration of exposure of the PVA solution with the metal precursors to microwave radiations is done. The heating process, which, upon the other hand, reduces the metal ions, facilitating the formation of CdS in the PVA matrix, takes minutes to achieve the creation of nanocomposites [9].

### C. Ex-situ Blending Method

The ex-situ method, which is less common for close mixing, involves the separate synthesis of nanoparticles of Ag and CdS using any standard colloid chemical pathway. These previously synthesised and often surface functionalised nanoparticles are then physically mixed with the PVA solution by vigorous stirring or ultrasonic treatment to achieve dispersion. The solution is then filmed. Preventing nanoparticle agglomeration during blending and producing a stable, homogenous composite are the primary challenges with this approach [10]. Table 1 lists the benefits and limitations of each approach and offers a summary of related literature.

**Table 1.** Summary of Synthesis Methods for CdS/Ag-PVA Nanocomposites

Synthesis Method	Key Process Details	Advantages	Disadvantages	Ref.
In-situ Chemical Reduction	Sequential addition of Ag <sup>+</sup> and Cd <sup>2+</sup> /S <sup>2-</sup> precursors to hot PVA solution.	Simple, low-cost, good control over composition.	Can lead to broader particle size distribution.	[7, 11]
Sol-Gel	Hydrolysis and condensation of precursors within PVA matrix.	Excellent homogeneity, high purity, fine dispersion.	Longer processing time, often requires catalysts.	[8, 12]
Microwave-Assisted	PVA+precursors solution irradiated with microwaves for 1-10 mins.	Extremely fast, energy-efficient, uniform heating.	Requires specialized equipment, scaling can be tricky.	[9, 13]
Ex-situ Blending	Pre-formed NPs are mixed with PVA solution via stirring/sonication.	Independent control of NP synthesis.	Poor dispersion, risk of agglomeration, weak interface.	[10, 14]

## RESULTS AND DISCUSSION

### Structural and Morphological Characterization

In materials science, it is critical to comprehend the relationship between structure and properties. To verify the effective formation of CdS and Ag nanoparticles, their dispersion within the PVA matrix, and the interaction between the various phases, a variety of characterization techniques are used.

#### A. X-ray Diffraction (XRD)

The crystalline phases of the embedded nanoparticles and the crystallinity of the nanocomposite films are both examined using XRD. Around  $2\theta = 19.5^\circ$ , which corresponds to its (101) plane, pure PVA usually exhibits a broad semi-crystalline peak. The thick halo is then filled with crystalline nanoparticles, which add sharp Bragg peaks. Typical peaks of the hexagonal (wurtzite) or cubic (zinc compound) phases of CdS can be seen. The plane (111), (220) and (311) represent the peaks of the cubic phase at approximately 26.5, 44 and 52 degrees (JCPDS Number 6) 10-0454 (EPC). Ag NPs' face-centered cubic (fcc) structure is confirmed by distinct peaks at  $2\theta \approx 38.1^\circ$  (111),  $44.3^\circ$  (200),  $64.4^\circ$  (220), and  $77.3^\circ$  (311). 04-0783). Successful doping is confirmed by the presence of two peaks in the nanocomposite formula. The Debye-Scherrer formula can be used to estimate the average size of the crystals, which usually results in a size of 5 to 20 nm, which is consistent with nanoscale formation [15]. As the nanoparticle load increases, the intensity of the PVA peak often decreases, indicating that the presence of the fillers has reduced the crystallinity of the polymer.

#### B. Fourier Transform Infrared (FTIR) Spectroscopy

FTIR spectroscopy, which looks at molecular vibrations and functional groups, shows that nanoparticles and PVA chains are chemically involved in the same way. Approximately  $3200\text{-}3600\text{ cm}^{-1}$  (O-H stretching),  $2900\text{ cm}^{-1}$  (C-H stretching),  $1420\text{ cm}^{-1}$  (C-H bending),  $1320\text{-}1350\text{ cm}^{-1}$  (C-H wagging),  $1090\text{ cm}^{-1}$  (C-O stretching), and  $850\text{ cm}^{-1}$  (C-C stretching) are the broad peaks in the FTIR spectrum of pure PVA. There are discernible changes in the location and strength of these peaks, especially the O-H and C-O stretches, upon doping with CdS and Ag. The complexation between PVA's hydroxyl groups and the surface ions of CdS and Ag nanoparticles is responsible for this. An O-H band shift or broadening indicates a hydrogen bonding interaction between the polymer matrix and the nanoparticles. When there are no new peaks, the interaction is usually physical (physisorption) as opposed to chemical (chemisorption) [16].

#### C. Scanning and Transmission Electron Microscopy (SEM/TEM)

Direct visual proof of the shape, size, and distribution of nanoparticles is offered by SEM and TEM. At lower loadings, SEM images of the nanocomposite surface frequently display a smooth and uniform morphology, while at higher concentrations, nanoparticles can be seen as clusters or scattered white spots (Ag). For acquiring comprehensive information at the nanoscale, TEM is essential. Lattice fringes corresponding to the d-spacing of CdS can be seen using high-resolution TEM (HRTEM) (e.g. G., 0.336 nm for the (111) plane of cubic CdS) and Ag (e. G. 0.236 nm for the plane (111)). The uniform distribution of Cd, S, and Ag elements throughout the PVA matrix can be visually

confirmed by elemental mapping using Energy-Dispersive X-ray Spectroscopy (EDS) in conjunction with SEM or TEM, confirming successful and homogeneous doping [17].

#### **D. UV-Visible Spectroscopy**

This is a crucial technique for analyzing the optical properties. Pure PVA usually has a featureless visible portion of its UV-Vis spectrum. When CdS is added, a distinct absorption edge is introduced in the 450–520 nm range, which corresponds to its bandgap energy. The precise location of this edge makes it possible to use Tauc's plot to calculate the optical bandgap, and quantum confinement effects in nanoparticles frequently cause a blue shift (~515 nm) in comparison to bulk CdS. A characteristic surface plasmon resonance (SPR) band, usually in the 400–450 nm range, is introduced by the addition of Ag NPs. This band is indicative of collective electron oscillations in metallic silver nanoparticles. Particle size, shape, and the local dielectric environment (the PVA matrix) all affect the band's position and width. The spectrum of a CdS/Ag-PVA nanocomposite is a superposition of the Ag SPR band and the CdS absorption edge. Moreover, a change in the CdS absorption or a shift in the Ag SPR peak may suggest an electronic interaction between the two nanomaterials [18].

#### **Properties of CdS/Ag-Doped PVA Nanocomposites**

PVA's properties are altered by the addition of CdS and Ag nanoparticles, producing improved and frequently unique qualities.

##### **A. Optical Properties**

The most obvious changes are to the optical characteristics. As was mentioned, the contributions from both CdS and Ag cause the nanocomposites to show strong absorption in the visible and UV spectrums. Tauc's plot is used to calculate the optical bandgap, which is found to decrease as the concentration of nanoparticles increases. This is explained by the introduction of localized states within the PVA bandgap and the creation of charge transfer complexes between the polymer and the nanoparticles. When Ag nanoparticles are present, the photoluminescence (PL) intensity of CdS is frequently reduced. For applications in photocatalysis and photovoltaics where a longer charge carrier lifetime is required, this quenching is a highly desirable phenomenon as it indicates effective energy or charge transfer from the excited CdS (donor) to the Ag nanoparticles (acceptor) [19].

##### **B. Electrical Properties**

An excellent insulator is pure PVA. Its electrical conductivity is greatly increased by the addition of highly conductive Ag nanoparticles and semiconducting CdS. As the temperature and filler content rise, so does the nanocomposite films' DC electrical conductivity. A thermally activated conduction mechanism is suggested by the conductivity's adherence to the Arrhenius equation. The nanoparticles' creation of interconnected conducting pathways within the insulating polymer matrix is what causes the increased conductivity. Ag's superior conductivity is the main factor responsible for this improvement. The AC conductivity and dielectric properties of these materials (dielectric constant, dielectric losses) are also strongly dependent on the

frequency and fill concentration, which makes them interesting for dielectric capacitor applications [20].

### C. Mechanical Properties

For flexible applications, the mechanical characteristics (elongation at break, Young's modulus, and tensile strength) are essential. There is a trade-off between mechanical strength and nanoparticle doping. Well-dispersed nanoparticles can function as reinforcing fillers at low concentrations, enhancing the modulus and tensile strength by mechanically interlocking with the polymer chains and limiting their mobility. Higher loadings, however, cause nanoparticles to clump together and serve as stress concentration sites that cause cracks and premature failure, lowering strength and flexibility. For mechanical reinforcement, the ideal loading is usually low (typically less than 5-8 weight percent) and is largely dependent on the dispersion quality and synthesis technique [21].

**Table 2.** Reported Properties of CdS/Ag-PVA Nanocomposites from Literature

NP Composition (in PVA)	Synthesis Metho	Key Findings	Application Focus	Ref.
CdS/Ag (5wt%)	<i>In-situ</i> chemical	Bandgap reduced from 5.8 eV (PVA) to 4.2 eV. Ag SPR at 425 nm. Enhanced electrical conductivity.	Optoelectronics	[22]
CdS/Ag (0.5-2wt% Ag)	Microwave	Spherical Ag NPs (10-15 nm), CdS NPs (5-8 nm). PL quenching observed. Excellent antimicrobial activity.	Antimicrobial coatii	[23]
CdS/Ag (4:1 ratio)	Sol-Gel	High homogeneity. 90% photocatalytic degradation of methylene blue under UV light in 60 min.	Photocatalysis	[24]
CdS/Ag (10wt%)	<i>Ex-situ</i> blending	Agglomeration observed. Dielectric constant increased by two orders of magnitude at low frequency.	Dielectric capacitor	[25]
CdS/Ag (1-3wt%)	<i>In-situ</i> casting	Tensile strength increased by ~40% at 2wt% loading. Decreased at higher loadings.	Flexible films	[26]

## Applications

Numerous cutting-edge applications are made possible by the multifunctionality of CdS/Ag-PVA nanocomposites.

### A. Photocatalysis

An excellent photocatalytic system is formed by the combination of CdS and Ag. CdS is the primary photoabsorber, and when light is irradiated, it produces electron-hole pairs. The photogenerated electrons are effectively scavenged from the conduction band of CdS by the Ag nanoparticles, which act as electron sinks. The rate of electron-hole recombination is significantly decreased by this process, resulting in an increased number of holes available for participation in oxidation reactions. Organic pollutants (dyes, pharmaceuticals, pesticides) in wastewater can be broken down into harmless compounds like CO<sub>2</sub> and H<sub>2</sub>O by these highly reactive species. Photocatalytic films,

unlike powdered catalysts, can be effortlessly deployed and recovered from treated water thanks to the PVA matrix, which is a more convenient method to utilize [27].

### **B. Antimicrobial Applications**

The strong antibacterial properties of Ag NFP are well-known. They can attach to the microbial cell walls, impair permeability and cause cell death by producing reactive oxygen species (ROS) and releasing ions of Ag<sup>+</sup>. When embedded in PVA, these nanoparticles provide a permanent release of antimicrobials, making the nanocomposite film ideal for active food packaging for extended shelf life or for wound dressings for preventing infections. In the presence of light, CdS may enhance this effect by photocatalytic generation of ROS, resulting in a dual-mode antimicrobial activity [28].

### **C. Optoelectronic Devices**

The tunable bandgap of these composites, the high absorption of visible light and the increased electrical conductivity make them promising for flexible optoelectronics. They can be used as active layers in heterojunction solar cells, as photodetectors converting light signals to electric current or as light emitting devices (LEDs). Flexibility and ease of processing of PVA allow for the production of devices on flexible substrates, which is a key requirement for modern wearables [29].

### **D. Radiation Shielding**

Recently, polymer nanocomposites have been studied for their ability to protect against ionising radiation, such as X-rays and gamma rays. The theory is based on the photo-electro-magnetic effect, which is proportional to the fourth atomic number ( $Z^4$ ) of the absorbent. The high- $Z$  elements in these compounds (Cd:  $Z=48$ , Ag:  $Z=47$ ) are much more effective than the low- $Z$  elements in polymers (C, H, O) in absorbing radiation. Therefore, PVA can significantly increase its radiation protection capacity by adding CdS and Ag, making it a flexible, lightweight and lead-free alternative to traditional protective materials in aerospace and medical applications [30].

### **Challenges and Future Perspectives**

Despite the significant progress, several challenges remain before these materials can be commercially produced on a laboratory scale.

#### **A. Toxicity and Environmental Concerns**

The presence of cadmium, a known heavy metal toxic, poses significant health and environmental risks, especially when it comes to the proper disposal of such materials after their useful life. Leaching of Cd<sup>2+</sup> ions from broken compounds could be a source of environmental risk. To stop leaching, future studies must concentrate on methods for fully encasing the CdS nanoparticles in the stable polymer matrix. Additionally, investigating less hazardous substitute semiconductors (e.g. G. ZnS, Bi<sub>2</sub>S<sub>3</sub>) while preserving performance is an important area of study.

#### **B. Agglomeration and Long-Term Stability**

It is still technically difficult to achieve and sustain a uniform dispersion of nanoparticles at high loadings. The properties of the composite may deteriorate due to agglomeration during synthesis or over time during application. To increase homogeneity and long-term stability, more efficient surface modifiers and

compatibilizers for nanoparticles must be developed, and synthesis methods such as those aided by ultrasound or microwave must be improved.

### C. Scalability and Cost

It is not easy to go from lab synthesis at the gram level to industrial production at the kilogram level. Three main obstacles are cost-effectiveness, process control, and reproducibility. For scalable production, automated continuous flow reactors and microwaves might be investigated. Despite being utilized in small amounts, the price of silver also plays a role in high-volume applications.

## CONCLUSION

**Fundamental Finding** : CdS/Ag-doped PVA nanocomposites demonstrate enhanced multifunctional performance due to the synergistic interaction between a flexible polymer host, a semiconductor, and a metal nanofiller, while synthesis methods and characterization techniques confirm controlled morphology, effective nanoparticle dispersion, and improved mechanical, optical, and electrical properties that enable broad interdisciplinary applications. **Implication** : The tailored properties of these nanocomposites position them as promising materials for antimicrobial coatings, environmental photocatalysis, flexible optoelectronics, and radiation shielding, indicating strong potential for advancing health, environmental, and next-generation technological solutions. **Limitation** : Commercialization remains constrained by challenges related to toxicity, scalability, and long-term stability. **Future Research** : Future studies should focus on overcoming these barriers through innovative material design and the development of eco-friendly alternatives to achieve meaningful practical impact.

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