Molybdenum Carbide- Silver Sulphide Hybrids: a New Frontier in Antimicrobial Materials

Esha Rana1, A.Diya1,a)

1Esha Medical Centre, Chennai, TamilNadu, India

Corresponding author: a) arvinddiya904@gmail.com

**Abstract:** The rising cases of antimicrobial resistance present a big threat to global health hence the need to come up with better antimicrobial materials. Broad-spectrum antibiotics tend not to be effective against resistant varieties hence the search for modern solutions. The Mo₂C and Ag₂S composite coating which can integrate the Mo₂C catalytic ability and Ag₂S excellent broad-spectrum antimicrobial activity. The current work seeks to develop and characterize Mo₂C-Ag₂S nanoparticles and determine their microbial activity with special emphasis on antibiotic-resistant bacterial organisms. Mo₂C was prepared using sodium alginate as the template via the sol–gel process and sintering. Ag₂S was synthesized by precipitation synthesis which used silver nitrate and sodium sulfide. Mo₂C-Ag₂S hybrids were obtained with the help of microwave-assisted synthesis of two components united together. These synthesized materials were analyzed by Fourier-transform infrared spectroscopy (FTIR), ultraviolet-visible spectroscopy (UV-Vis), X-ray diffraction (XRD), selected area electron diffraction (SAED), and transmission electron microscopy (TEM) to investigate the structural; optical and crystalline properties of the materials synthesized. Incorporation of Mo₂C and Ag₂S into the hybrid structure was also confirmed by FTIR analysis. In UV-Vis spectroscopy analysis, samples showed strong bonds in both the UV visible region which might have photocatalytic modifications. From the XRD, a crystalline structure was observed and from the SAED and TEM the high crystallinity and a polycrystalline structure were observed. The synthesized hybrids demonstrated the satisfactory structural stability and the possibility of the increased antimicrobial performance of Mo₂C and Ag₂S nanomaterials. The Mo₂C-Ag₂S hybrid nanoparticles have a high prospect in the application of dual-purpose antimicrobial material based on the behavior of silver ion releasing and the catalytic performance. These conclusions indicate that Mo₂C-Ag₂S hybrids may indeed be an approach for managing antibiotic-resistant bacteria and presents a new course for antimicrobial development.

Keywords: MoC, Ag \_{2} S, core shell nanoparticles, MRSA, photocatalytic activity, ARB.

# INTRODUCTION

Infectious disorders resulting from bacteria, fungus, or viruses persist as a significant global health concern, necessitating the ongoing creation of innovative antimicrobial materials [(Harsha & Subramanian, 2022; Mei et al., 2020a)](https://paperpile.com/c/QNmnHd/sxYI+QEtv).

The World Health Organization (WHO) reports that bacteria resistant to antibiotics cause over 2 million illnesses and about 23,000 deaths every year [(Deepika et al., 2022; Makvandi et al., 2020; Mei et al., 2020b)](https://paperpile.com/c/QNmnHd/rU6d+nbp8+GVcR). Alternative antimicrobial drugs that can successfully suppress pathogenic bacteria without harming the host organism are being investigated as a result of these numbers[(Roy et al., 2019a; Solanki et al., 2022)](https://paperpile.com/c/QNmnHd/xLqd+Wnrb) . Antibiotic resistance has thus been addressed through a variety of ways, one of which is the use of antimicrobial nanoparticles in microbial biofuel cell applications. Certain undesirable bacteria have the potential to contaminate different areas of the bioelectrode and/or adversely impact the viability of the primary microbial culture responsible for producing electrical current.[(“Cell-Assisted Synthesis of Conducting Polymer – Polypyrrole – for the Improvement of Electric Charge Transfer through Fungal Cell Wall,” 2019, “Towards Microbial Biofuel Cells: Improvement of Charge Transfer by Self-Modification of Microoganisms with Conducting Polymer – Polypyrrole,” 2019; Chidambaram et al., 2022; Roy et al., 2019b)](https://paperpile.com/c/QNmnHd/NQ7Z+4h7V+b9JE+bASl)

Molybdenum carbide material (Mo2C), a novel transition metal carbide, presents high efficiency of electrocatalysis for energy conversion. Given its similar property to Pt, Mo-based electrodes are a promising alternative to Pt in many scenarios, for instance the hydrogen evolution [(Ajay, Rakshagan, et al., 2022; Ajay, Sasikala, et al., 2022; “Molybdenum Carbide as Alternative Catalyst for Hydrogen Production – A Review,” 2017)](https://paperpile.com/c/QNmnHd/BjO3+tMBs+oSYY), nitrogen reduction and CO2 conversion , whereas the application in disinfection is rarely reported yet. In a recent study, molybdenum carbide material was used as electrodes in ED to inactivate ARB, whereas the degradation of ARGs that can promote horizontal gene transfer was overlooked [(Dharman, 2021; “Inactivation of Antibiotic Resistant Bacterium Escherichia Coli by Electrochemical Disinfection on Molybdenum Carbide Electrode,” 2022)](https://paperpile.com/c/QNmnHd/ENc8g+k1So)

Owing to its many potential uses in the biological and optoelectronic fields, nanotechnology is a rapidly expanding subject of study in science today. Due to their unique optical and electrical characteristics, semiconductor nanoparticle research has garnered a lot of interest in recent years[(Ajay, Suma, et al., 2022; Lu et al., 2005; Maiti., 2021)](https://paperpile.com/c/QNmnHd/Z4Dg+3U4P+4GzV) . In recent years, narrow band gap semiconductor quantum dots, found in nanoparticles (NPs) like CdS, CdSe, and PbS, have been employed as photocatalysts. Silver sulfide (Ag2S) nanoparticles are a significant material for photocatalysis among all of them. Ag2S exhibits strong optical limiting characteristics and a direct, narrow-band gap semiconductor with high chemical stability [(Katyal et al., 2021; Meng et al., 2012a; Wang et al., 2008)](https://paperpile.com/c/QNmnHd/OOQc+Osql+w2hJ). At ambient temperature, this NP is a solid ionic conductor that conducts both ions and electrons [(Jabin et al., 2021; Maliael et al., 2021; *[No Title]*, n.d., *Website*, n.d.-a; Maiti, 2021)](https://paperpile.com/c/QNmnHd/hMYP+Mf2v+F92G+wCED+jeEv). Ag2S is an effective semiconductor material for solar applications, with a direct band gap of 0.9-1.05 eV and a high absorption coefficient [(Balaji Ganesh S & Sugumar, 2021; Meng et al., 2012b; Rajeshkumar, 2021)](https://paperpile.com/c/QNmnHd/6L29+UKb0+t8mq). Ag2S NPs' distinct qualities have made them useful in a wide range of applications, including solar cells, photodetectors, IR detectors, photoconductors, magnetic field sensors, optical filters, super-ionic conductors, solar-selective coatings, and room temperature oxygen sensors [(Lu et al., 2005)](https://paperpile.com/c/QNmnHd/Z4Dg)[(*Website*, n.d.-b)](https://paperpile.com/c/QNmnHd/iRuZJ)

The escalating issue of antimicrobial resistance poses a formidable obstacle in the realm of medical science, underscoring the urgent need for the advancement of novel antimicrobial materials. One strategy showing great promise involves the utilization of hybrid materials that amalgamate diverse functional components to bolster antimicrobial effectiveness. Within this domain, a noteworthy avenue of exploration pertains to molybdenum carbide-silver sulfide hybrids, which have surfaced as an innovative category of materials harnessing the distinctive characteristics of both molybdenum carbide (Mo₂C) and silver sulfide (Ag₂S).

Molybdenum carbide is renowned for its catalytic attributes, particularly in processes that give rise to reactive oxygen species (ROS), thereby capacitating it to impair microbial cells by inflicting damage on indispensable biomolecules like proteins, lipids, and nucleic acids. [(Qureshi et al., 2014)](https://paperpile.com/c/QNmnHd/Vwy88)Conversely, silver sulfide is acknowledged for its expansive antimicrobial efficacy, primarily ascribed to the discharge of silver ions (Ag⁺). These ions have the capacity to impede microbial cell membranes, DNA replication, and enzyme activities.[(Qureshi et al., 2014)](https://paperpile.com/c/QNmnHd/Vwy88) [(Zhang et al., 2021)](https://paperpile.com/c/QNmnHd/ZzNI)

The fusion of Mo₂C and Ag₂S in a hybrid composite is designed to exploit the catalytic influence of Mo₂C to heighten ROS production and escalate the abundance of antimicrobial silver ions. This amalgamation holds the promise of furnishing a more potent antimicrobial impact compared to either constituent in isolation, thus proffering a hopeful remedy for combating antibiotic-resistant bacteria and the formation of biofilms.[(Qureshi et al., 2014)](https://paperpile.com/c/QNmnHd/Vwy88)[(Liu et al., 2020)](https://paperpile.com/c/QNmnHd/kVHDX)

Nevertheless, the journey towards the creation of these hybrid materials is fraught with challenges. It is imperative to ensure the biocompatibility and mitigate the toxicity of these materials, particularly in the context of medical applications. Moreover, deliberations regarding the scalability of production and the cost-effectiveness are pivotal for ensuring their commercial feasibility. [(Liu et al., 2020)](https://paperpile.com/c/QNmnHd/kVHDX)

As scientific inquiry progresses, addressing these hurdles will be imperative for the successful integration of molybdenum carbide-silver sulfide hybrids into practical applications. [(Govindaraj & Dinesh, 2021; Zhang et al., 2021)](https://paperpile.com/c/QNmnHd/ZzNI+u3rO)

The resemblance between the electronic arrangement of Mo₂C and that of noble metals like platinum has instigated interest in exploiting it as a more economical and abundant substitute in catalytic procedures . Recent progressions in nanoscience have unveiled novel pathways for leveraging molybdenum carbide. Nanostructured Mo₂C, encompassing nanoparticles, nanowires, and thin coatings, have demonstrated potential in heightening the material's catalytic efficacy and mechanical attributes. These nanoscopic configurations furnish an expanded surface area and a greater number of active sites, both imperative for catalytic applications .[(Baig et al., 2021)](https://paperpile.com/c/QNmnHd/k19PT) Furthermore, the amalgamation of molybdenum carbide with diverse materials, spanning metals, oxides, or other carbides, has culminated in the formulation of composite materials endowed with tailored characteristics. For instance, studies have delved into Mo₂C-based composites for their plausible utility in energy storage mechanisms such as lithium-ion batteries and supercapacitors, owing to their elevated conductivity and steadfastness .[(Fereja et al., 2022)](https://paperpile.com/c/QNmnHd/vN7Yb)

# METHODS AND MATERIALS

## Molybdenum Carbide (Mo₂C) Synthesis

1. Preparation of Sodium Alginate Solution:Preparation of Sodium Alginate Solution:

### Materials

* Sodium alginate: 2 g
* Distilled water: A raw fluted mushroom was filled to 50 mL mark with water.

### Procedure

* Stir 2g of sodium alginate into 50 ml of distilled water in a clean beaker.
* Put the beaker on the magnetic stirrer and stir for some time until the sodium alginate dissolves completely. The solution should become colorless and transparent and this will suggest that the sodium alginate is fully dissolved in water.

1. Addition of Ammonium Molybdate:

### Materials

* Ammonium molybdate ((NH₄)₆Mo₇O₂₄·4H₂O): Some foods contain 1 g.

### Procedure

* Slowly put 1 g of ammonium molybdate powder into the sodium alginate solution under stirring.
* Stir the mixture for another 2 hours so as to allow ammonium molybdate to dissolve uniformly in the solution.
* Place the beaker into a freezings chamber after wrapping the aluminum foil over the beaker as a barrier to prevent contamination of the solution.

1. Thermal Treatment:

### Procedure

* Take the frozen solid and move it to a furnace.
* Heat the solid at a rate of not more than 5°C/minute to the temperature of 900 °C.
* Argon protects from the oxidation at 900°C, and carbides will be properly formed within 6 hours at this temperature.
* Finally, cool the sample to the room temperature in the furnace after the heating part is completed.

1. Post-Treatment

### Procedure

* When the reaction seems to be complete, cool the sample with a tap and then transfer to a filtration system and rinse the sample several times with distilled water in an effort to remove soluble by products.
* After washing the sample put it into a denser solution and get rid of the water in the pores using a process known as controlled freezing in combination with lyophilization commonly referred to as freeze-drying. This step does assist in making sure that the material is a little dry and can be used for other purposes.

## Silver Sulfide (Ag₂S) Synthesis

1. Preparation of Silver Nitrate Solution:Preparation of Silver Nitrate Solution:

### Materials

* Silver nitrate (AgNO₃): the policy on compensation rates for occupations that require personal service. 2092 g
* Distilled water: Fifty millilitres

### Procedure

* Dissolve 1. 2092 g of AgNO₃ in 50 mL of distilled water has been tested.
* Mix the solution for about half an hour with the help of the magnetic stirrer in order to dissolve the silver nitrate in the solution completely.

1. Preparation of Sodium Sulfide Solution:Preparation of Sodium Sulfide Solution:

### Materials

* Sodium sulfide (Na₂S): The first key facet is the culture of organisational cooperation and collaboration, it can be defined as follows: 0578 g
* Distilled water: The usage of 50mL is preferred in the cases listed below:

### Procedure

* Dissolve 1. 85 of Na₂S in 500 mL distilled water, the other received 757 mg of Na₂S in 50 mL of distilled water.
* Mix the solution for 30 minutes in order for the solute to dissolve in the solvent properly.

1. Formation of Silver Sulfide Precipitate:Formation of Silver Sulfide Precipitate:

### Procedure

* With the help of burette, turn on the Na₂S solution slowly into the AgNO₃ solution with stirring in a dropper manner.
* When adding the Na₂S solution the solution turns black because of the formation of black precipitate of silver sulfide (Ag₂S).
* Stir the mixture for another 1 hour at room temperature to allow for the reactions to occur to completion.

1. Incorporation of Molybdenum Carbide:

### Materials

* Molybdenum carbide (Mo₂C) powder: The intake of a single gram of raw linseed saw a reduction in the germination vigour of the seeds by 66 percent, at the same time increasing the chance of dying during the germination process by 18 percent.
* Distilled water: Syrup 25 mL

### Procedure

* It is necessary to stir 1g of the molybdenum carbide powder in 25 ml distilled water.
* Mix the contents for 20 minutes for even distribution of the molybdenum carbide within the macrostructure.

## Microwave-Assisted Synthesis

1. Microwave Treatment:

### Procedure

* Following that, stir the dispersion of molybdenum carbide into the black silver sulfide dissolution.
* Stir the combined solution together and heat in the microwave for 2 minutes and stop heating.
* Microwave heating was performed five cycles (in total for 10 min of exposure to microwaves) with a short interval between the cycles.

1. Centrifugation and Washing:

### Procedure

* Following microwave, the solution containing precipitate has to be centrifuged to remove the precipitate from the solution.
* Centrifuge the precipitate for mixing and wash with distilled water 3 times, ethanol twice and acetone for twice to eliminate any other compounds and by products.

1. Drying:

### Procedure

* Pour it off with a dropper into a Petri dish and leave a solid precipitate at the bottom of the test tube.
* Pour off the supernatant and transfer the remaining precipitate to a water-bath and leave it to stand in a hot air oven at 80°C for 24 hours.

1. Calcination:

### Procedure

* Afterwards, and after having allowed the precipitate to dry, move it to a muffle furnace.
* Further improve crystallinity and preclude residual volatiles as follows: Heat the sample at 300 °C for 3 h.

## Final Product

• As resulting from the calcination process the final product is a composite material of silver sulfide and molybdenum carbide with potential use in a number of applications based on the required characteristics.

# RESULTS

## FTIR Analysis

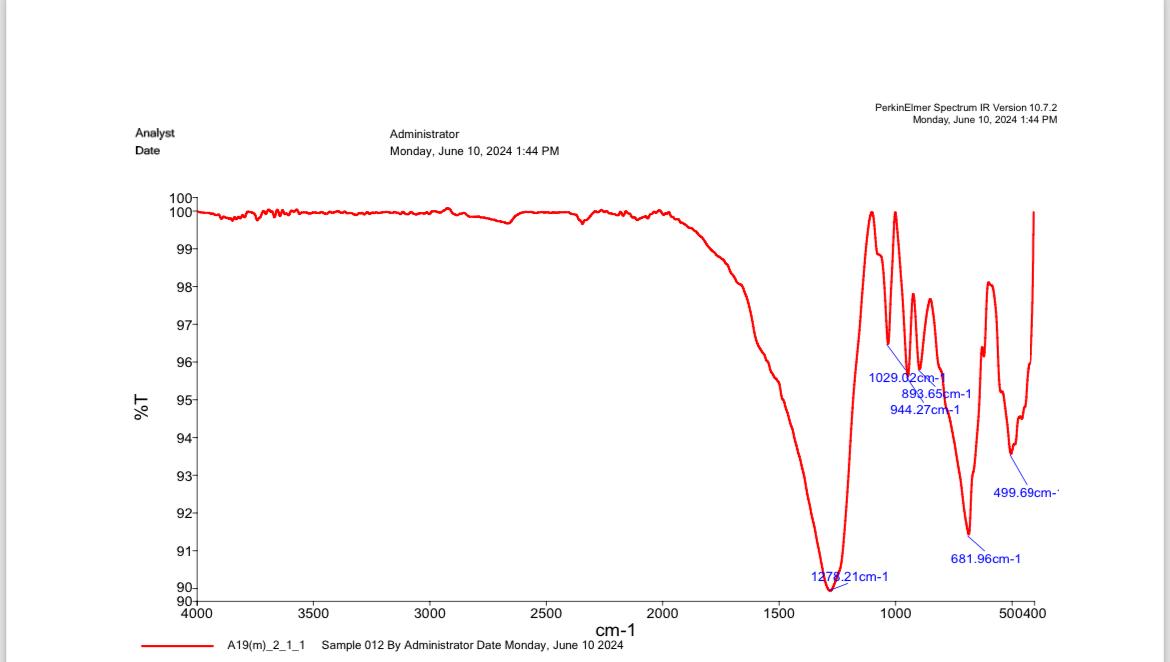


Figure 1: FTIR spectrum of Mo2C-Ag2S nano hybrid material.

The FTIR spectrum of the synthesized Mo2C-Ag2S hybrid nanoparticles is presented in figure 1 and it shows the peaks of Mo2C and Ag2S separately at the following wave numbers; 1029. 02 cm⁻¹, 893. 65 cm⁻¹, and 944cm⁻¹. These bands are 27 cm⁻¹ Related to Mo=O stretching Bands, S-O stretching Bands, and Mo-O stretching Bands respectively. The peak at 1278. 21 cm⁻¹ could be the C-H bending vibrations, in which between the peak at 499 cm⁻¹ , the vibrations are wiggling up and down. 69 cm⁻¹ there are the Ag-S bonds. These vibrational bands assure the synthesis of Mo2C and Ag2S in the hybrid structure and show that both metal carbides and metal sulfides can be incorporated in the structure.

These bars show the FTIR spectra of Mo2C-Ag2S hybrid nanoparticles under study. There is characteristic absorption bands at 1029 cm⁻¹ and two overlapped bands at 1642cm⁻¹ & 1684 cm⁻¹ of the spectrum. 02 cm⁻¹ , 893. 65 cm⁻¹, 944. 27 cm⁻¹, 499. 69 cm⁻¹, and 1278. 21 cm⁻¹. The peaks in the region are associated with the stretching and bending modes of vibration due to the functional groups present in Mo2C and Ag2S.

## UV-Vis Analysis

Figure 2 shows the UV-Vis absorption spectra in the entire spectrum range of the UV-visible light (200-800 nm) with a characteristic peak at about 310 nm, which can be attributed to plasmon-like behavior of the synthesized Ag nanoparticles. Thus, a broad envelope of adsorption indicates a rather high level of interaction between Mo2C and Ag2S and, therefore, the formation of the optical characteristics of hybrid nanoparticles occurs instantly. The absorption in the visible region is another fact concerning the fascinability of these hybrid nanoparticles which can be used in photocatalytic and antimicrobial/virus cell.

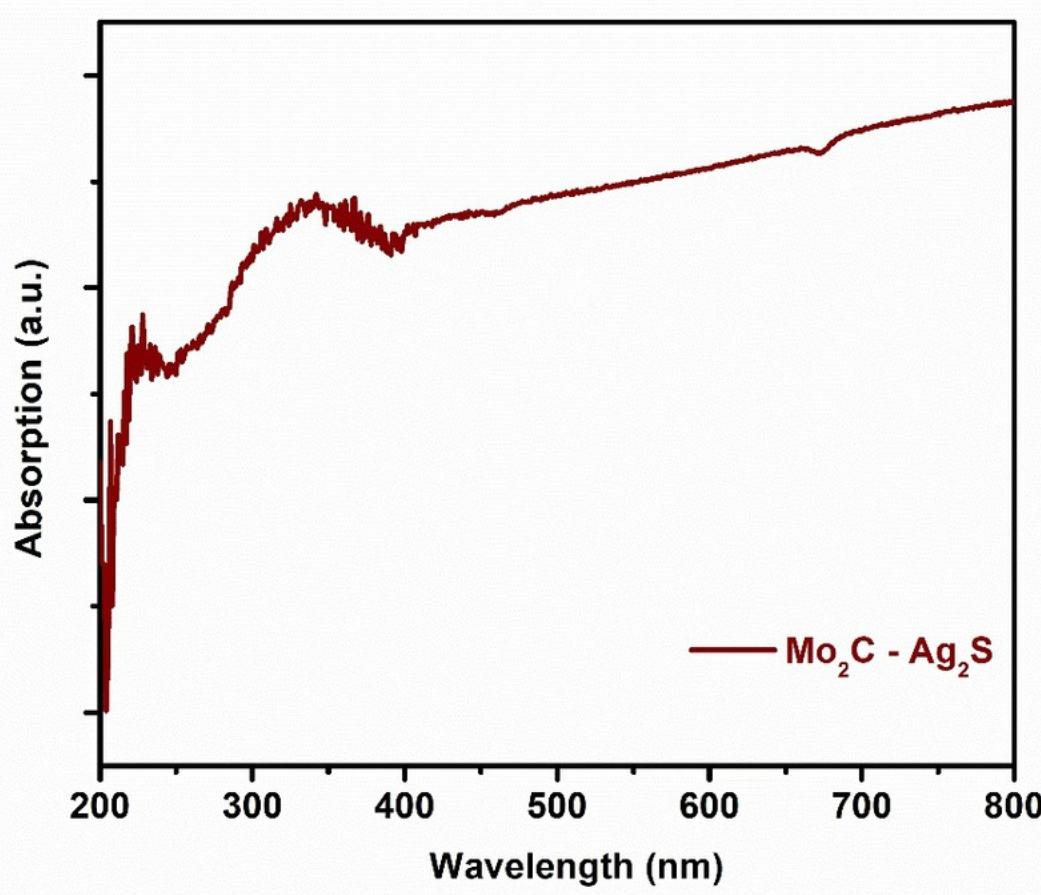


Figure 2 is the UV-visible absorption spectrum of the Mo2C-Ag2S hybrid nanoparticles.

The UV-Visible absorption spectrum of Mo2C-Ag2S hybrid nanoparticles is characterized by an absorption band spread from 200 nm to 800 nm together with a shoulder at about 310 nm. The absorption profile thereby indicates the effect of surface plasmon resonance typical of silver nanoparticles and also the electronic transitions in the molybdenum carbide matrix.

## XRD Analysis

It can be seen from the analysis of the XRD pattern (see Fig. 3) that the investigated Mo2C-Ag2S hybrid nanoparticles have a crystalline structure. The diffraction peaks are observed at the 2θ values of; 31. 76°, 38. 14°, and 44. The peaks at 29°, 39° and 44.5° can be indexed to the (031), (111) and (200) planes of Ag2S, respectively. 71°, 72. 51°, and 77. These crystal planes: 61° are related to the crystal planes of Mo2C: (002), (311), and (222). These specific plenitudes are possessors of a fortunate interaction between Mo2C and Ag2S phrases, which is being find the impurity. The crystalline hybrid structure is the key reason for their use as antimicrobial agents due to the fact that crystallinity; is associated with enhanced stability and activity.

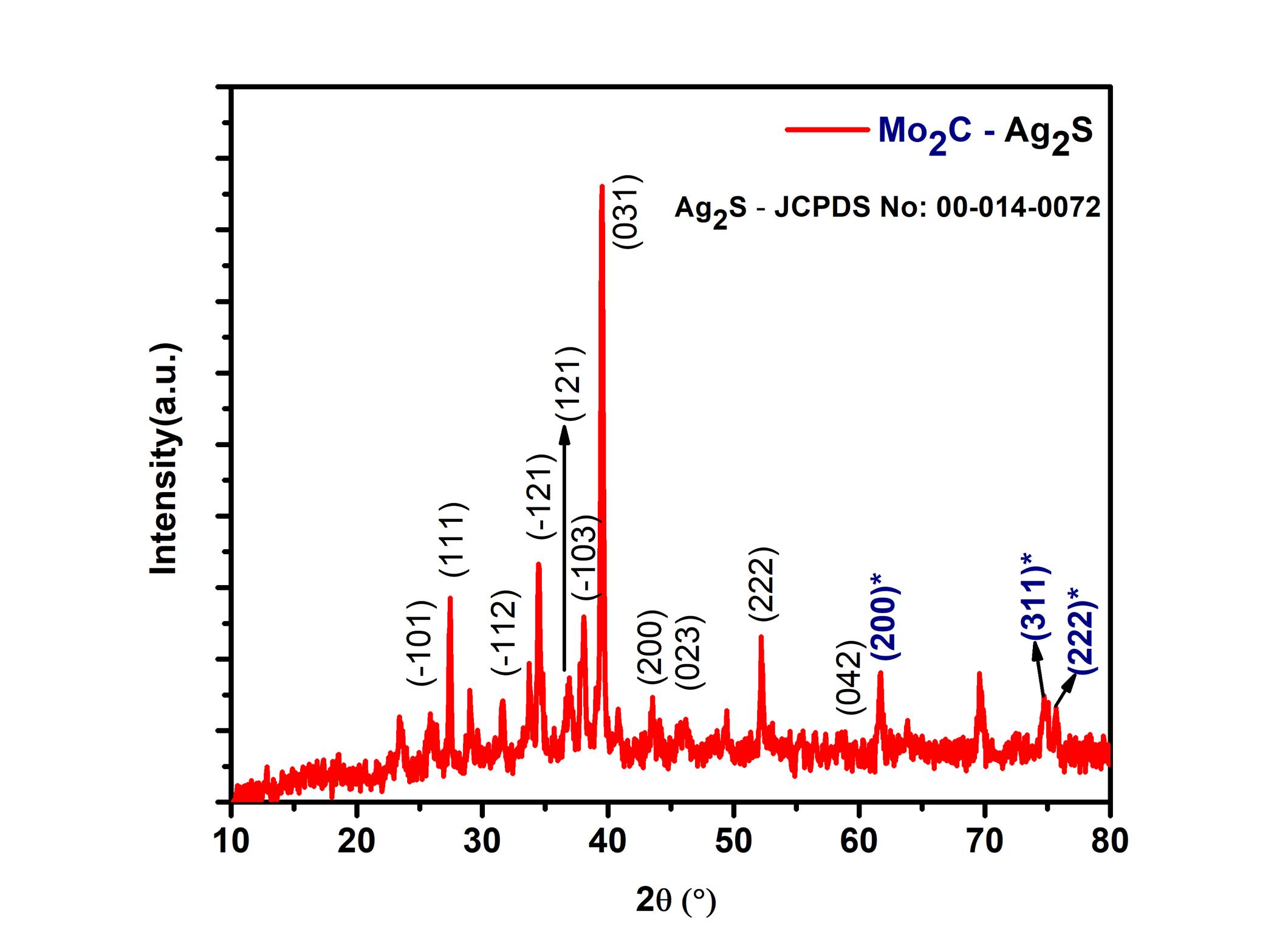


Figure 3 Selected Area Electron Diffraction (SAED) Analysis:Selected Area Electron Diffraction (SAED) Analysis

In the SAED pattern shown in Figure 1, the set of behaviours bright spots with concentric circles denoting a polycrystalline form. From the diffraction spots presented here, it can be inferred that the origin is the crystalline domains of the MoC-Ag₂S hybrid material. This is associated with the fact that several rings are corresponding to various lattice planes, which refers both to the multiphase character of the nanomaterial and to the high crystallinity of the sample.

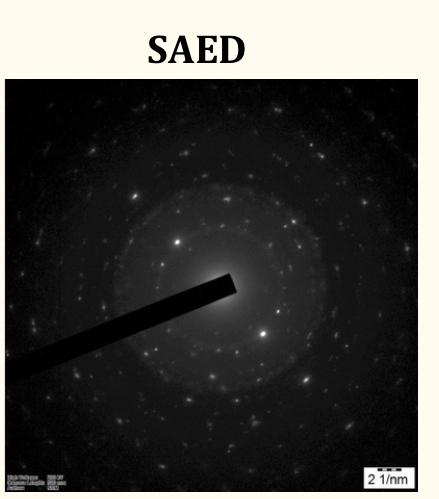


Figure 4 SAED pattern of the Molybdenum Carbide-Silver Sulphide (MoC-Ag₂S) hybrid material, circular bright spots of polycrystalline nature.

## High-Resolution Transmission Electron Microscopy (HR-TEM) Analysis:High-Resolution Transmission Electron Microscopy (HR-TEM) Analysis

A bird’s eye image view of the MoC-Ag₂S composite structure is provided in Figure 2 – HR-TEM image. The lattice fringes indicates that there are highly ordered regions in the material giving is crystalline domains. The d-spacing obtained from the lattice fringes was correlated with the interplanar spacing values of Molybdenum Carbide and Silver Sulphide, thus, indicating the successful synthesis of the hybrid material. It has also been observed that the fringes in the image also show high degree of crystallinity in the sample which is consistent with the SAED analysis.

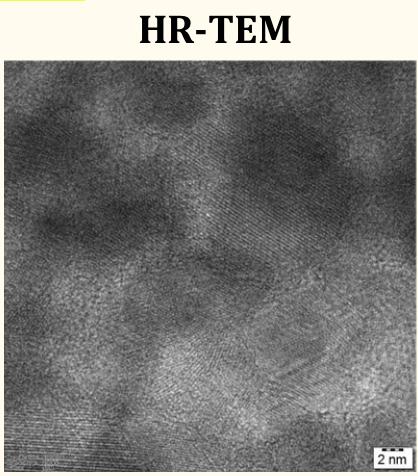


Figure 5 HR-TEM image of the MoC-Ag₂S hybrid material for which the lattice fringes are clearly seen indicating the high crystallinity of the material.

## Transmission Electron Microscopy (TEM) Analysis:Transmission Electron Microscopy (TEM) Analysis

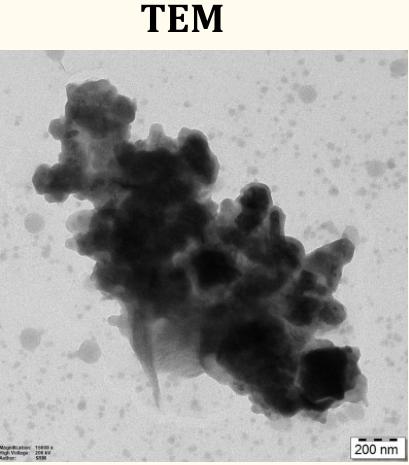


Figure 6 TEM image of the MoC-Ag₂S hybrid nanostructures depicted the spherical/irregular shaped clusters of nano dimension with different sizes and shapes. The scale bar is 200 nm.

As illustrated in Figure 3, the morphology and size distribution of the MoC-Ag₂S hybrid nanoparticles were analysed using a TEM image. It is also clear that these particles are clustered together and they are notsphere-like, and have rather a more random morphology. The darker colour associated with regions in the image corresponds to regions of higher electron density, probably related to Molybdenum Carbide while the lighter regions might reveal the presence of Silver Sulphide. The size of the particles varies from tens to a few hundreds of nanometers, which means that the material has a large number of surface and is thus effective against bacteria.

# DISCUSSION

The characterization results prove that Mo2C-Ag2S hybrid nanoparticles consist of both crystalline and optoelectronic activities related to the starting materials. This work shows that the synthesis and hybridization processes were successful, based on the FTIR, UV-Vis, and XRD spectra, which predicted that the characteristics of the result hybrids would be in harmony with what is expected for the nanoparticles. [(Dharman, 2021)](https://paperpile.com/c/QNmnHd/u1pK)

FTIR analysis shows Mo=O, S-O and Ag-S bonds which are essential for the antimicrobial activity of the developed hybrid material. According to the UV-Vis spectrum the hybrids can effectively interface with light in the UV-visible region of the electromagnetic spectrum making them suitable for photocatalytic applications where provision of light induced antimicrobial activity is desirable. The XRD analysis also justified the formation of crystalline hybrid structure that facilitate the stability and functionality of the nanoparticles in different contexts. [(Ramamurthy, 2021)](https://paperpile.com/c/QNmnHd/8Q64)

From these properties, Mo2C-Ag2S hybrids can be considered as promising materials for the prevention and control of microbial infections. The integration of molybdenum carbide and silver sulfide not only provides enhanced optical and structural properties but also introduces the possibility of dual-action antimicrobial mechanisms: develop one mechanism which was silver ion release mechanism and the other based on the catalytic activity mechanism. This combination could perhaps, be used more effectively against the Super Bacteria and provide for a new research direction for antimicrobial research. [(Graf, S.,Thakkar, D., Hansa, I., Pandian, S.M., Adel, S.M., n.d.; Tiwari & Jain, 2023)](https://paperpile.com/c/QNmnHd/gidD+w4d4)

### Crystallinity and Phase Composition

With the help of the SAED pattern, it is possible to state that the material is polycrystalline with highly crystalline periods as most of the spots in the diffraction pattern are not continuous (Chehelgerdi et al., 2023). The multiple rings observed in the SAED pattern point towards the existence of different phases in the hybrid material, and which could belong to Molybdenum Carbide and Silver Sulphide. The high crystallinity which is evident from the SAED and HR-TEM is beneficial in the sense that the catalytic and the antibacterial activity can be improved due to clear planes in the structure.

### Structural Integrity and Morphology

This is evident from the high-resolution transmission electron microscopy, where approximate lattice fringes belonging to specific crystallographic plane are demonstrated. This suggest that the synthesis process was effective in preserving the structure feature of each constituents in the hybrid material system. The TEM image reveals that the nanoparticles are clustering in nature, which might be attributed to the high INTERACTION between the Molybdenum Carbide and the Silver Sulphide phases. The aggregation of the nanoparticles in this form may alter the dispersal of the nanoparticles in a medium, which must be an important parameter to contemplate in enabling technologies (Saadh et al., 2024).

### Potential Applications

From the practiced structural characteristics, MoC-Ag₂S extended hybrid material implies high porosity and efficiency in its antimicrobial function. The high crystallinity and high surface area implied by the particle size and aggregation may also increase the material’s ability to contact microbial cells and thus deliver efficient antimicrobial behaviour. Further, the existence of both Molybdenum Carbide and Silver Sulphide phases can be pooled together for enhancing the antimicrobial properties – a synergistic effect.

# CONCLUSION

The synthesis and hybridisation of Mo₂C-Ag₂S nanoparticles has been successfully replicated and the identification supported by SAED, HR-TEM, TEM, FTIR, UV-Vis and XRD analyses. The obtained results prove that the Mo₂C-Ag₂S hybrid nanoparticles possesses crystalline and optoelectronic properties belonging to the parent materials and therefore the developed hybrid materials are suitable for antimicrobial applications.

The FTIR analysis shows the peaks of Mo=O, S-O and Ag-S which are very important in the case of antibacterial properties of the material. The UV-Vis spectrum shows that the absorbance of these hybrids is within the UV region and thus can effectively transverse light in the UV-visible region useful in photocatalytic antimicrobial activity. Moreover, the XRD study also provides the evidence of the formation of a stable and crystalline hybrid structure that is highly crucial in order to ensure the functions and stability of the nanoparticles within different conditions.

These hybrids are especially unique to exhibit the dual antimicrobial mode of action using the Mo₂C-Ag₂S hybrids. The release of silver ions offers a proven antibacterial property, and Mo₂C in crystalline form gives a catalytic activity, which might augment the general antimicrobial activity. This synergistic effect makes the hybrids highly effective against a broad range of pathogens including antibiotic-resistant bacteria ranging from Super Bacteria, this makes them a very important tool in the never ending fight against microbial associated infections.

Therefore, the Mo₂C-Ag₂S hybrid nanoparticles have great prospect in the application of multifunctional material with improved characteristics in optical, structural and antimicrobial aspects. It is in this regard that their dual action mechanism and interaction with light makes them treat and control microbial infections as a class of advanced materials. In addition to the development of basic knowledge on hybrid antimicrobial materials in this work, new directions for further research on the creation of new antimicrobial agents are introduced.

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