

Silver oxide nanoparticle-decorated $\text{Ti}_3\text{C}_2\text{T}_x$ MXene nanocomposites for biomedical applications: Antibacterial activity, wound healing, cancer therapy, biosafety, and future perspectives

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Abstract

The rapid emergence of multidrug-resistant microorganisms and the growing demand for multifunctional biomedical materials have increased interest in hybrid nanocomposites with enhanced antibacterial, therapeutic, and diagnostic performance. Among these materials, silver oxide nanoparticles (Ag_2O NPs) have attracted considerable attention due to their broad-spectrum antimicrobial activity, reactive oxygen species generation, and potential biomedical functionality. However, their practical application is often limited by aggregation, uncontrolled ion release, stability concerns, and dose-dependent cytotoxicity. MXenes, particularly $\text{Ti}_3\text{C}_2\text{T}_x$ MXene, offer a promising platform for overcoming these limitations because of their large surface area, hydrophilic surface terminations, excellent conductivity, photothermal conversion ability, and ease of surface modification. The integration of Ag_2O nanoparticles with MXene nanosheets can produce a synergistic nanocomposite with improved dispersion, enhanced antibacterial efficiency, controlled bioactivity, and potential utility in wound healing, infection control, cancer therapy, biosensing, and smart biomedical coatings. This review discusses the structural features, synthesis strategies, biomedical mechanisms, and therapeutic potential of Ag_2O -decorated $\text{Ti}_3\text{C}_2\text{T}_x$ MXene nanocomposites. Special emphasis is placed on antibacterial mechanisms, including silver ion release, oxidative stress, bacterial membrane disruption, and MXene-assisted photothermal effects. The review also highlights wound-healing applications, anticancer potential, biosensing opportunities, and major biosafety challenges associated with Ag_2O /MXene systems. Finally, current limitations, including long-term toxicity, MXene oxidation, reproducibility, scalability, and clinical translation, are critically discussed. Overall, Ag_2O /MXene nanocomposites represent an emerging class of biomedical nanomaterials with strong potential for next-generation antimicrobial and therapeutic platforms.

Keywords: MXene, Ag NPs, biomedical application, nanomedicine, biosensors.

Nanocompósitos de MXene $\text{Ti}_3\text{C}_2\text{T}_x$ decorados com nanopartículas de óxido de prata para aplicações biomédicas: atividade antibacteriana, cicatrização de feridas, terapia contra o câncer, biossegurança e perspectivas futuras

Resumo

O rápido surgimento de microrganismos multirresistentes e a crescente demanda por materiais biomédicos multifuncionais têm aumentado o interesse por nanocompósitos híbridos com desempenho antibacteriano, terapêutico e diagnóstico aprimorado. Entre esses materiais, as nanopartículas de óxido de prata (Ag_2O NPs) têm atraído considerável atenção devido à sua ampla atividade antimicrobiana, à capacidade de gerar espécies reativas de oxigênio e ao potencial funcional para aplicações biomédicas. No entanto, sua aplicação prática é frequentemente limitada pela agregação das nanopartículas, liberação descontrolada de íons de prata, problemas

de estabilidade e citotoxicidade dependente da dose. Os MXenes, especialmente o MXene $\text{Ti}_3\text{C}_2\text{T}_x$, oferecem uma plataforma promissora para superar essas limitações devido à sua elevada área superficial, terminações superficiais hidrofílicas, excelente condutividade elétrica, capacidade de conversão fototérmica e facilidade de modificação superficial. A integração de nanopartículas de Ag_2O com nanofolhas de MXene pode produzir um nanocompósito sinérgico com melhor dispersão, maior eficiência antibacteriana, bioatividade controlada e potencial de aplicação na cicatrização de feridas, no controle de infecções, na terapia contra o câncer, no biossensoriamento e em revestimentos biomédicos inteligentes. Esta revisão discute as características estruturais, as estratégias de síntese, os mecanismos de ação biomédica e o potencial terapêutico dos nanocompósitos de MXene $\text{Ti}_3\text{C}_2\text{T}_x$ decorados com Ag_2O . É dada especial ênfase aos mecanismos antibacterianos, incluindo a liberação de íons de prata, o estresse oxidativo, a desestabilização da membrana bacteriana e os efeitos fototérmicos mediados pelo MXene. A revisão também destaca as aplicações na cicatrização de feridas, o potencial anticancerígeno, as oportunidades em biossensoriamento e os principais desafios relacionados à biossegurança dos sistemas $\text{Ag}_2\text{O}/\text{MXene}$. Por fim, são discutidas criticamente as limitações atuais, incluindo a toxicidade a longo prazo, a oxidação dos MXenes, a reprodutibilidade, a escalabilidade dos processos de produção e os desafios para a tradução clínica. De modo geral, os nanocompósitos $\text{Ag}_2\text{O}/\text{MXene}$ representam uma classe emergente de nanomateriais biomédicos com elevado potencial para o desenvolvimento de plataformas antimicrobianas e terapêuticas de próxima geração.

Palavras-chave: MXene, nanopartículas de Ag, aplicação biomédica, nanomedicina, biossensores.

1. Introduction

The increasing prevalence of microbial infections delays wound healing, and antimicrobial resistance has created an urgent need for advanced biomedical materials that can simultaneously prevent infection, support tissue repair, and reduce dependence on conventional antibiotics (Gul et al., 2025). Antimicrobial resistance occurs when microorganisms no longer respond effectively to antimicrobial medicines, making infections more difficult to treat and increasing the risk of disease spread, severe illness, and mortality (Amir et al., 2025). This challenge is particularly important in biomedical environments such as wound dressings, implant surfaces, surgical materials, biosensors, and drug-delivery platforms, where bacterial colonization and biofilm formation can severely limit treatment outcomes (Zhu et al., 2024).

As a result, researchers are increasingly exploring multifunctional nanomaterials that combine antibacterial, anti-inflammatory, photothermal, diagnostic, and regenerative properties in a single platform. Metal oxide nanoparticles have emerged as one of the most important classes of antimicrobial nanomaterials because of their chemical stability, tunable physicochemical properties, high surface-area-to-volume ratio, and ability to interact directly with microbial cells. Common metal oxide nanoparticles used in biomedical and antimicrobial research include zinc oxide, titanium dioxide, copper oxide, iron oxide, cerium oxide, and silver oxide nanoparticles (Kashif et al., 2024a). These nanomaterials can be engineered by controlling their particle size, morphology, crystallinity, surface charge, porosity, and surface functional groups, which strongly influence their biological activity (Chetry et al., 2025).

Compared with many conventional organic antimicrobial agents, metal oxide nanoparticles often show improved stability and broad-spectrum activity, making them attractive for infection control, wound dressing, coatings, biosensing, and therapeutic applications (Jamal et al., 2024). The antimicrobial performance of metal oxide nanoparticles is generally associated with multiple mechanisms rather than a single biological target. These mechanisms include the generation of reactive oxygen species, disruption of bacterial cell membranes, release of toxic metal ions, interaction with proteins and nucleic acids, interference with cellular respiration, and induction of oxidative stress. Reactive oxygen species can damage bacterial membranes, proteins, and DNA, which may reduce the likelihood of resistance development compared with antibiotics that act on highly specific biochemical pathways (Kashif et al., 2024b).

This multi-target antibacterial behavior makes metal oxide nanoparticles especially useful against multidrug-resistant bacteria and biofilm-associated infections. However, their biomedical translation remains limited by several concerns, including nanoparticle aggregation, uncontrolled ion release, possible cytotoxicity toward mammalian cells, poor long-term stability in physiological environments, and inconsistent performance under different biological conditions. Among metal oxide nanoparticles, silver oxide nanoparticles have attracted growing attention because of their strong antimicrobial activity and potential biomedical relevance (Del Toro et al., 2022). Silver-based nanomaterials are widely studied for antibacterial, antifungal, antiviral, wound-healing, biosensing, medical coating, and drug-delivery applications (Harun-Ur-Rashid et al., 2025; Shah et al., 2024a).

Silver oxide nanoparticles are especially interesting because they can release bioactive silver ions and participate in oxidative stress-related antibacterial processes (Shah et al., 2024a). Studies on Ag₂O nanoparticles have reported antibacterial effects against both Gram-positive and Gram-negative bacteria, including clinically relevant strains such as *Staphylococcus aureus* and *Escherichia coli*. Their antimicrobial activity is generally attributed to the combined effects of Ag⁺ ion release, membrane disruption, intracellular oxidative damage, enzyme inhibition, and interference with microbial metabolic pathways (Deng et al., 2025).

Despite these advantages, the direct use of silver oxide nanoparticles in biomedical systems presents important limitations (Deng et al., 2025). Free Ag₂O nanoparticles may aggregate in biological media, reducing their active surface area and leading to uneven biological responses. Their uncontrolled dissolution may cause excessive Ag⁺ release, which can improve antibacterial action but may also increase cytotoxicity toward host cells at higher concentrations (Sun et al., 2024a). In addition, the stability, dispersion, and biological selectivity of Ag₂O nanoparticles must be improved before they can be reliably applied in wound dressings, implant coatings, antimicrobial hydrogels, or therapeutic platforms (Sun et al., 2025). Therefore, hybridization with suitable support materials has become an important strategy for improving the performance and safety of silver oxide nanoparticles (Azam et al., 2025; Shah et al., 2024b).

MXenes represent a rapidly expanding family of two-dimensional transition metal carbides, nitrides, and carbonitrides (Shah et al., 2024b). They are generally expressed by the formula $M_{n+1}X_nT_x$, where M represents an early transition metal, X represents carbon or nitrogen, and T_x represents surface terminations such as –O, –OH, and –F. Among them, Ti₃C₂T_x is the most widely investigated MXene for biomedical applications because of its layered two-dimensional structure, large specific surface area, hydrophilic surface chemistry, high electrical conductivity, mechanical flexibility, and strong photothermal conversion ability. MXenes have been explored in antibacterial materials, wound dressings, biosensors, drug delivery, cancer photothermal therapy, tissue engineering, and smart biomedical devices (Zeng et al., 2025).

The biomedical value of MXenes arises from their ability to function not only as passive nanocarriers but also as active therapeutic components. Their large surface area allows efficient loading and dispersion of nanoparticles, drugs, polymers, biomolecules, and metal ions. Their surface terminations provide sites for chemical modification and interaction with biological molecules. Their electrical conductivity supports biosensing and electroactive tissue-engineering applications, while their strong near-infrared light absorption enables photothermal therapy and light-triggered antibacterial activity. Ti₃C₂T_x MXene has also demonstrated antibacterial activity against both Gram-negative and Gram-positive bacteria, with mechanisms linked to direct membrane contact, sharp nanosheet edges, oxidative stress, and photothermal effects (Sun et al., 2022).

The combination of silver oxide nanoparticles with Ti₃C₂T_x MXene offers a promising strategy for developing multifunctional antimicrobial biomedical nanocomposites. In this hybrid system, MXene can act as a two-dimensional support that improves the dispersion of Ag₂O nanoparticles, reduces nanoparticle aggregation, increases interfacial contact with microbial cells, and provides additional antibacterial and photothermal functions (Li et al., 2025).

At the same time, Ag₂O nanoparticles can enhance the antimicrobial potency of MXene through silver ion release and oxidative stress-mediated bacterial killing. This combination may produce synergistic effects, where the antibacterial activity of the composite is greater than that of either Ag₂O nanoparticles or MXene alone. Such synergy is particularly valuable for biomedical applications requiring rapid bacterial inactivation, biofilm suppression, controlled therapeutic action, and compatibility with soft materials such as hydrogels, polymer membranes, and wound dressings (Jamil et al., 2025).

Ag₂O-decorated Ti₃C₂T_x MXene nanocomposites are especially relevant for wound-healing and infection-control applications. Infected wounds require materials that can eliminate bacteria, reduce inflammation, absorb exudate, maintain a moist healing environment, support cell migration, and promote tissue regeneration. MXene-based wound-healing materials have been reported to show potential in antibacterial therapy, smart wound monitoring, photothermal treatment, and tissue repair (Sun et al., 2024b). When combined with Ag₂O nanoparticles, MXene-based systems may provide dual antibacterial action through contact-mediated bacterial damage and Ag⁺-mediated biochemical disruption. Under near-infrared irradiation, the photothermal behavior of MXene may further enhance bacterial killing by locally increasing temperature, weakening bacterial membranes, and improving the sensitivity of microorganisms to silver-based antimicrobial effects (Hao et al., 2022; Wang et al., 2026).

Beyond wound healing, Ag₂O/MXene nanocomposites may also contribute to other biomedical fields, including antimicrobial coatings, biosensors, cancer therapy, and drug-delivery systems (Wang et al., 2026). The

conductive nature of $\text{Ti}_3\text{C}_2\text{T}_x$ MXene makes it suitable for electrochemical biosensing, while silver oxide nanoparticles may improve signal response and provide antimicrobial protection to the sensing interface. In cancer-related applications, MXenes can act as photothermal agents, whereas silver oxide nanoparticles may contribute cytotoxic and oxidative stress-related effects (Muhammad et al., 2026). However, these therapeutic possibilities require careful evaluation because cytotoxic mechanisms that are useful against bacteria or cancer cells may also damage healthy mammalian cells if dose, exposure time, and material stability are not properly controlled (Butler et al., 2023; Jia et al., 2026).

Therefore, the development of Ag_2O /MXene biomedical nanocomposites must balance antimicrobial efficiency with biosafety. Key safety concerns include silver ion over-release, oxidative stress in normal cells, MXene oxidation, long-term biodegradation, immune response, biodistribution, and possible accumulation in tissues. The biological response of these materials depends strongly on synthesis method, particle size, surface charge, Ag_2O loading, MXene flake size, surface functionalization, and the presence of stabilizing polymers or biomolecules. For this reason, future research should focus not only on improving antibacterial activity but also on establishing standardized toxicity testing, long-term stability analysis, in vivo validation, and scalable synthesis strategies (Jia et al., 2026).

Overall, silver oxide nanoparticle-decorated $\text{Ti}_3\text{C}_2\text{T}_x$ MXene nanocomposites represent an emerging class of multifunctional biomedical materials. By integrating the antimicrobial activity of Ag_2O nanoparticles with the high surface area, conductivity, hydrophilicity, and photothermal properties of MXene, these hybrid systems may offer new opportunities for infection control, wound healing, biosensing, and therapeutic nanomedicine (Su et al., 2026). This review therefore aims to discuss the fundamental properties of metal oxide nanoparticles and MXenes, the rationale for combining Ag_2O nanoparticles with $\text{Ti}_3\text{C}_2\text{T}_x$ MXene, and the biomedical significance of developing multifunctional antimicrobial nanocomposites for next-generation healthcare applications.

2. Silver Oxide Nanoparticles

2.1 Synthesis and Biomedical Relevance

Silver oxide nanoparticles (Ag_2O NPs) are an important class of silver-based metal oxide nanomaterials with growing relevance in antimicrobial and biomedical research (Gul et al., 2025; Zahoor et al., 2026). Their interest arises from the combination of nanoscale surface reactivity, silver-ion-related bioactivity, oxidative stress generation, and broad-spectrum antimicrobial potential (Muhammad et al., 2025a). In comparison with bulk silver oxide, Ag_2O nanoparticles possess a much larger surface-area-to-volume ratio, which increases their interaction with microbial membranes, biological fluids, proteins, and cellular components (Muhammad et al., 2025b).

This high surface reactivity makes them attractive for biomedical applications such as antibacterial wound dressings, antimicrobial coatings, infection-control materials, biosensing platforms, drug-delivery systems, and anticancer research (Shang et al., 2024). Reviews and experimental studies describe Ag_2O NPs as relatively easy to produce and as promising antimicrobial candidates, although their biological performance depends strongly on synthesis method, particle size, morphology, surface chemistry, dose, and exposure conditions.

Table 1. Silver oxide nanoparticles: synthesis and biomedical relevance.

Aspect	Key points	Biomedical relevance	Limitation/concern	References
Green synthesis	Ag_2O nanoparticles can be synthesized using plant extracts, phytochemicals, microbes, or natural biomolecules as reducing, capping, and stabilizing agents. Green synthesis is considered eco-friendly and may reduce toxic chemical residues.	Useful for biomedical applications because biomolecule-capped Ag_2O NPs may show improved dispersion, surface stability, and possible biocompatibility. Green routes are	Batch-to-batch variation can occur because plant extracts differ in chemical composition, pH, and phytochemical content. This may affect particle size, morphology, and biological activity.	Muhammad et al. (2023)

		especially suitable for wound dressings, hydrogels, and antimicrobial coatings.		
Chemical synthesis	Commonly involves precipitation or controlled reaction of silver salts under alkaline conditions, often using stabilizers or capping agents to control particle growth.	Provides better control over particle size, crystallinity, and reproducibility compared with many green methods. It is useful for preparing Ag ₂ O NPs for controlled incorporation into MXene, polymers, or coatings.	Residual chemicals must be removed carefully before biomedical testing. Harsh reaction conditions or toxic stabilizers may reduce biocompatibility.	Ali et al. (2025)
Morphology and size	Ag ₂ O NPs may appear as spherical, quasi-spherical, cubic, irregular, or aggregated particles depending on synthesis conditions. Particle size and shape influence surface area, Ag ⁺ release, ROS generation, and interaction with bacterial cells.	Smaller and well-dispersed particles usually provide greater bacterial contact and stronger antimicrobial performance. Uniform Ag ₂ O loading on Ti ₃ C ₂ T _x MXene can reduce aggregation and improve antibacterial efficiency.	Very small particles may show stronger cytotoxicity because of higher surface reactivity and faster ion release. Aggregated particles may show reduced antimicrobial activity.	Muhammad et al. (2026)
Ag ⁺ release	Ag ₂ O NPs can release Ag ⁺ ions in aqueous or biological environments. Ag ⁺ can bind to bacterial proteins, enzymes, membranes, and DNA.	Ag ⁺ release is one of the main antibacterial mechanisms. It can disturb membrane permeability, inhibit respiration, interfere with DNA replication, and disrupt protein function.	Excessive Ag ⁺ release may damage mammalian cells, delay wound healing, and increase oxidative stress. Controlled release is essential for biomedical safety.	Ur Rehman et al. (2025)
ROS generation	Ag ₂ O NPs can promote reactive oxygen species generation, including superoxide radicals, hydroxyl radicals, and hydrogen peroxide.	ROS can damage bacterial membranes, proteins, lipids, and genetic material, leading to bacterial death. This multi-target action may help against resistant bacteria.	Excess ROS can also damage fibroblasts, keratinocytes, and endothelial cells, which are important for tissue repair.	Ghani et al. (2023)

Antimicrobial activity	Ag ₂ O NPs show antibacterial and antifungal potential. Their activity is associated with Ag ⁺ release, ROS formation, membrane disruption, and metabolic inhibition.	Relevant for infected wound dressings, antimicrobial coatings, biomedical textiles, implant surfaces, and biofilm-control materials. Ag ₂ O has been reviewed as a promising antimicrobial candidate with relatively easy production and strong antibacterial activity.	Antimicrobial performance depends strongly on dose, particle size, exposure time, bacterial strain, and test method. Standardized antibacterial assays are needed.	Gul et al. (2024)
Biofilm inhibition	Ag ₂ O NPs may inhibit early bacterial attachment and interfere with mature biofilm structure through ion release, oxidative stress, and membrane damage.	Important for chronic wounds, burns, diabetic ulcers, and implant-related infections, where biofilms protect bacteria from antibiotics and immune response.	Mature biofilms are difficult to remove completely. Combining Ag ₂ O with MXene photothermal activity may improve antibiofilm performance.	Hussain et al. (2026)
Cytotoxicity	Cytotoxicity is dose-dependent and influenced by Ag ⁺ release, ROS generation, particle size, surface charge, and exposure time.	At optimized concentrations, Ag ₂ O NPs may be useful as antimicrobial agents while maintaining acceptable cell compatibility.	High concentrations can harm mammalian cells through oxidative stress, mitochondrial damage, membrane injury, and inflammation. Careful toxicity testing is required.	Khan et al. (2025)
Relevance to Ag ₂ O/MXene composites	Ti ₃ C ₂ T _x MXene can act as a two-dimensional support for Ag ₂ O NPs, improving dispersion and reducing aggregation.	The hybrid may combine Ag ₂ O-based Ag ⁺ /ROS antibacterial activity with MXene's high surface area, conductivity, hydrophilicity, and photothermal behavior.		Irfan et al. (2024)

Source: Authors, 2026.

2.2 Green synthesis of Ag₂O nanoparticles

Green synthesis has become one of the most widely explored approaches for preparing Ag₂O nanoparticles because it avoids or reduces the use of toxic reducing agents, stabilizers, and solvents (Li et al., 2026). In this method, biological materials such as plant extracts, bacteria, fungi, algae, or natural polymers act as reducing, capping, and stabilizing agents. Plant-mediated synthesis is particularly attractive because plant extracts contain

phytochemicals such as flavonoids, phenolic compounds, alkaloids, tannins, terpenoids, proteins, and carbohydrates, which can participate in silver-ion reduction, nanoparticle nucleation, and surface stabilization (Zhang et al., 2026a).

These biomolecules can also form an organic coating around the nanoparticles, improving colloidal stability and sometimes enhancing biological compatibility. Recent reviews of green silver nanoparticle synthesis emphasize that pH, temperature, reaction time, precursor concentration, extract concentration, and phytochemical composition are major parameters controlling nanoparticle size, stability, and yield. A typical green synthesis route begins with the preparation of an aqueous or ethanolic plant extract, followed by mixing with a silver precursor such as silver nitrate or silver sulfate (Zhang et al., 2026b).

The bioactive compounds in the extract promote nucleation and growth of Ag₂O nanoparticles, while simultaneously limiting uncontrolled aggregation. A 2024 *Scientific Reports* study synthesized Ag₂O nanoparticles using *Phragmanthera macrosolen* leaf extract, where the extract functioned as a reducing, capping, and stabilizing agent. The authors reported Ag₂O formation using AgNO₃ and plant extract without requiring harsh chemical reducing agents, and characterization was performed using SEM, HR-TEM, XRD, FTIR, EDS, and UV–visible spectroscopy (Zhao et al., 2025). This example demonstrates why green synthesis is highly relevant for biomedical materials: it can produce biofunctional nanoparticles under milder conditions and may introduce surface-bound organic molecules that influence antimicrobial and cytotoxic behavior. Green synthesis is especially useful when Ag₂O nanoparticles are intended for integration with MXene, hydrogels, chitosan, cellulose, alginate, or other biomaterial platforms.

The presence of natural capping molecules can improve nanoparticle dispersion and may reduce direct cytotoxicity by moderating surface reactivity (Kashif et al., 2026). However, green synthesis also has limitations. Plant extracts are chemically complex and variable, which can reduce reproducibility between batches. Differences in plant species, harvesting conditions, solvent type, extract concentration, and reaction pH can lead to changes in nanoparticle size, shape, crystallinity, and biological activity (Li et al., 2026). Therefore, green synthesis is environmentally attractive, but biomedical translation requires strict control of synthesis parameters and standardized characterization.

2.3 Chemical synthesis of Ag₂O nanoparticles

Chemical synthesis remains important because it offers better control over reaction conditions, particle formation, crystallinity, and reproducibility. The most common chemical method for Ag₂O nanoparticle synthesis is precipitation from a silver salt, usually AgNO₃, using an alkaline reagent such as NaOH or KOH. In a simplified reaction, Ag⁺ ions react with hydroxide ions to form silver oxide precipitates. Stabilizers or capping agents such as polyethylene glycol, polyvinylpyrrolidone, citrate, starch, or other polymers may be added to regulate particle growth and reduce aggregation (Li et al., 2025).

Reports on chemical precipitation describe Ag₂O nanoparticles prepared from AgNO₃ and NaOH, while other studies have used silver nitrate in the presence of polymeric stabilizers such as PEG. Chemical routes allow researchers to tune nanoparticle morphology by adjusting pH, precursor concentration, temperature, stirring time, solvent composition, surfactant concentration, and post-synthesis heat treatment. For example, chemical precipitation followed by thermal treatment has been used to study how annealing temperature affects the morphology and crystal structure of Ag₂O nanoparticles (Del Toro et al., 2024).

This is important for biomedical applications because the biological activity of Ag₂O nanoparticles is strongly linked to their size, crystallinity, shape, oxidation state, and surface charge. Smaller particles generally provide greater surface contact and may release Ag⁺ more readily, but they may also show higher cytotoxicity. Larger or highly aggregated particles may show reduced antimicrobial activity due to a lower accessible surface area.

Compared with green synthesis, chemical synthesis can be more reproducible and scalable, but it may involve residual chemicals that require careful washing and purification before biomedical testing. For Ag₂O/MXene nanocomposites, chemical synthesis can be adapted into an in situ deposition method, where Ag₂O nanoparticles are nucleated directly on Ti₃C₂T_x MXene nanosheets (Sun et al., 2025). This approach can improve interfacial contact between Ag₂O and MXene, prevent nanoparticle aggregation, and create a more uniform hybrid platform for antimicrobial, wound-healing, and biosensing applications.

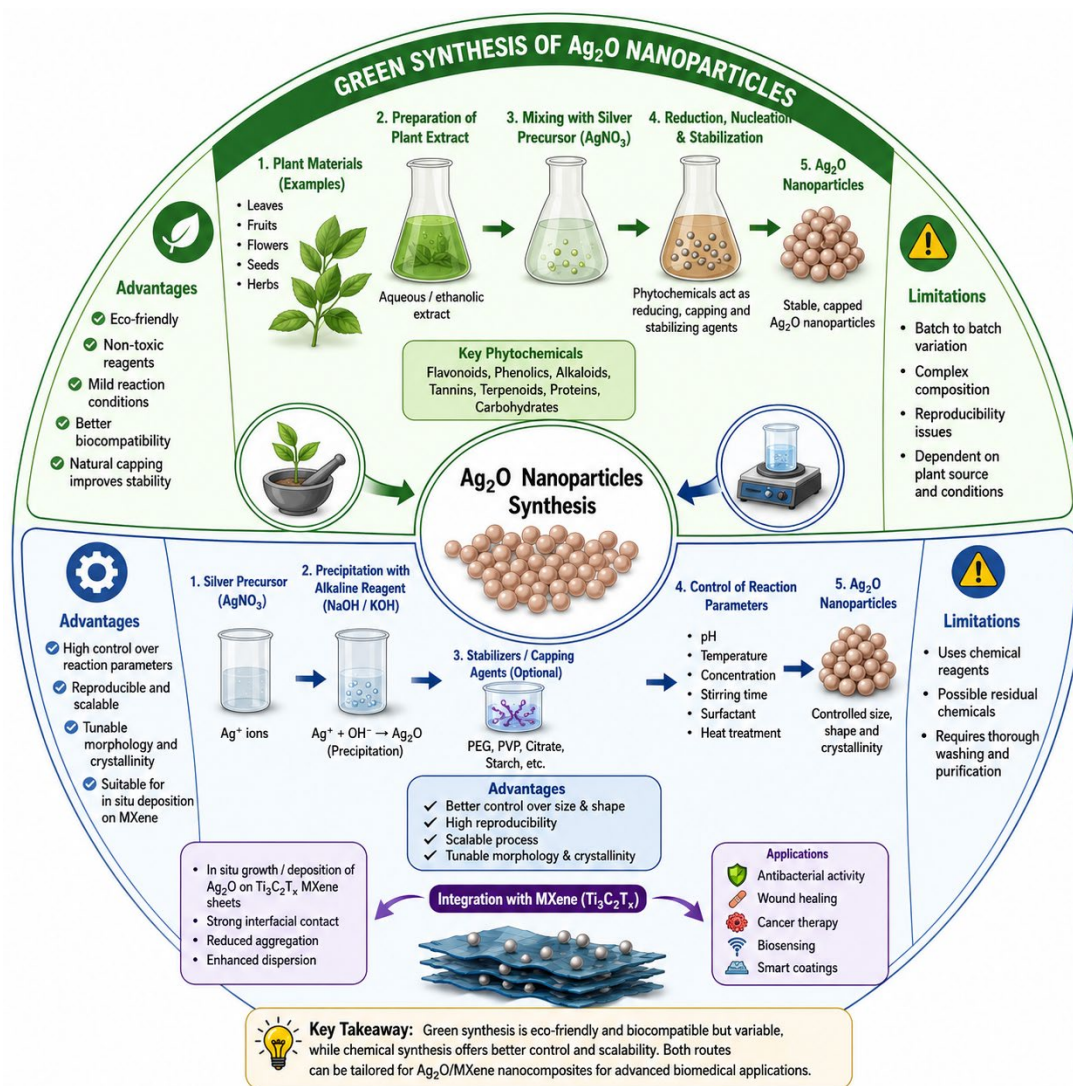


Figure 1. Explaining the general mechanism of synthesis of silver NPs. Source: Authors, 2026.

2.4 Morphology and physicochemical properties

The morphology of Ag_2O nanoparticles is a critical factor controlling their biomedical performance. Reported Ag_2O nanostructures include spherical particles, quasi-spherical particles, cubic particles, irregular particles, nanoclusters, and nanoparticle aggregates. Morphology is commonly evaluated using scanning electron microscopy and transmission electron microscopy, while crystalline phase is usually confirmed by X-ray diffraction. Other characterization methods include FTIR for surface functional groups, EDS for elemental composition, UV–visible spectroscopy for optical properties, XPS for oxidation state, zeta potential for colloidal stability, and dynamic light scattering for hydrodynamic size (Kashif et al., 2024a).

The surface chemistry of Ag_2O nanoparticles determines how they interact with bacteria, mammalian cells, proteins, and biomaterial matrices. Positively charged or partially ion-releasing silver oxide surfaces can interact with negatively charged bacterial membranes, increasing membrane permeability and cellular damage. At the same time, biomolecule-coated Ag_2O nanoparticles may interact differently because surface-bound organic groups can reduce direct contact, improve dispersion, or modify protein corona formation. In Ag_2O /MXene systems, the two-dimensional MXene sheet can serve as a support that distributes Ag_2O nanoparticles across a large surface area, reduces agglomeration, and increases contact with microbial cells. Controlled growth of silver oxide particles on layered supports has been reported, and particle morphology has been linked to antibacterial performance through the release of Ag^+ , which acts as an antibacterial agent. Morphological control is therefore essential for

biomedical use. An ideal Ag₂O nanoparticle system should have controlled particle size, narrow distribution, stable dispersion, reproducible surface chemistry, and predictable Ag⁺ release. In wound dressings or coatings, excessive aggregation may reduce antibacterial efficiency, while uncontrolled dissolution may increase toxicity. For this reason, Ag₂O nanoparticles are often incorporated into polymers, hydrogels, porous scaffolds, or two-dimensional supports such as MXene to improve stability and regulate biological activity (Kashif et al., 2026b).

2.5 Ag⁺ release and antibacterial mechanism

The biomedical activity of Ag₂O nanoparticles is closely associated with the release of Ag⁺ ions. Silver ions are highly reactive toward biological molecules and can interact with thiol, phosphate, amino, and carboxyl groups in proteins, enzymes, membranes, and nucleic acids. In bacteria, Ag⁺ ions can disrupt membrane integrity, inhibit respiratory enzymes, interfere with DNA replication, alter protein function, and disturb cellular metabolism. Broader silver nanoparticle literature shows that silver-based antibacterial action is strongly linked to continuous Ag⁺ release, electrostatic attraction to bacterial membranes, increased membrane permeability, and intracellular biochemical disruption (Shah et al., 2024).

For Ag₂O nanoparticles, Ag⁺ release is especially relevant because silver oxide can act as a silver-ion source under aqueous or biological conditions. Controlled Ag⁺ release is beneficial because it provides sustained antibacterial activity. However, excessive release may damage mammalian cells, delay tissue repair, or induce inflammatory responses. Therefore, one of the major design goals in Ag₂O-based biomedical materials is to achieve a balance between sufficient ion release for bacterial killing and limited ion release for host-cell safety. MXene-supported Ag₂O nanoparticles may help regulate this balance by improving particle dispersion, reducing uncontrolled aggregation, and enabling surface functionalization with polymers or biomolecules (Khan et al., 2025).

2.6 ROS generation and oxidative stress

Reactive oxygen species generation is another important mechanism in the antimicrobial activity of Ag₂O nanoparticles. ROS such as superoxide radicals, hydroxyl radicals, singlet oxygen, and hydrogen peroxide can damage bacterial membranes, oxidize proteins, disrupt lipids, and induce DNA damage. In silver-based nanoparticles, ROS generation often occurs together with Ag⁺ release and membrane disruption. Reviews of silver nanoparticle antibacterial mechanisms report that Ag⁺ release can promote membrane disruption, ROS production, inhibition of protein synthesis, and interference with DNA replication (Zahoor et al., 2026).

In bacterial cells, oxidative stress can overwhelm antioxidant defense systems and cause irreversible cellular injury. This multi-target mechanism is one reason silver-based nanoparticles are considered promising against resistant bacteria. Unlike many antibiotics that target specific bacterial pathways, Ag₂O nanoparticles may attack bacteria through several simultaneous routes: membrane damage, ion toxicity, oxidative stress, enzyme inhibition, and genetic material disruption. This broad mechanism may reduce the probability of resistance development, although resistance and tolerance to silver-based materials remain possible and should not be ignored (Muhammad et al., 2023).

ROS generation is also relevant to anticancer research because cancer cells are often more sensitive to oxidative stress than normal cells. However, ROS is a double-edged mechanism. While oxidative stress can be useful for destroying bacteria or cancer cells, excessive ROS can damage healthy mammalian cells, impair fibroblast activity, and interfere with normal wound healing. Therefore, Ag₂O nanoparticles intended for biomedical use must be evaluated carefully using both antimicrobial assays and mammalian cytotoxicity assays (Ahmad et al., 2026).

3. Biological Activities

3.1 Antimicrobial activity

Ag₂O nanoparticles have demonstrated antimicrobial activity against both Gram-positive and Gram-negative bacteria. Their effectiveness is commonly evaluated using agar well diffusion, disk diffusion, minimum inhibitory concentration, minimum bactericidal concentration, time-kill assays, biofilm inhibition assays, live/dead staining, and membrane leakage studies. In the 2024 *Scientific Reports* study on biosynthesized Ag₂O nanoparticles, antibacterial activity was tested against *Staphylococcus aureus* and *E. coli*, and the authors reported low MIC values compared with commercially available particles. Another study on biosynthesized Ag₂O nanoparticles reported antibacterial activity against biofilm-forming bacteria and attributed bacterial death to membrane damage

and release of intracellular constituents, including proteins.

The antibacterial response may differ between Gram-positive and Gram-negative bacteria because of differences in cell-wall architecture. Gram-negative bacteria possess an outer membrane and relatively thin peptidoglycan layer, while Gram-positive bacteria have a thicker peptidoglycan wall. Reviews on silver nanoparticles report that antimicrobial efficiency can vary between these bacterial groups, partly because wall structure affects nanoparticle penetration, ion access, and membrane damage. For wound-healing applications, this broad-spectrum behavior is important because infected wounds often contain mixed bacterial populations, including *S. aureus*, *E. coli*, *Pseudomonas aeruginosa*, and other opportunistic pathogens.

Ag₂O nanoparticles may also contribute to antibiofilm activity. Biofilms are difficult to treat because bacterial cells are protected by an extracellular polymeric matrix that limits antibiotic penetration and supports persistent infection. Silver-based nanoparticles can interfere with biofilms by damaging bacterial membranes, inhibiting growth, reducing metabolic activity, and disrupting extracellular matrix formation. For Ag₂O/MXene nanocomposites, the combination of Ag⁺ release, ROS production, direct nanosheet contact, and possible MXene photothermal activity may provide stronger antibiofilm performance than Ag₂O alone (Madani et al., 2021).

3.2 Biomedical relevance

The main biomedical relevance of Ag₂O nanoparticles lies in infection control. They can be incorporated into wound dressings, hydrogels, polymer films, implant coatings, textile materials, biosensor surfaces, and drug-delivery systems. In wound dressings, Ag₂O nanoparticles may reduce microbial burden and prevent infection, while the surrounding matrix provides moisture retention, mechanical protection, and tissue support (Elahi et al., 2021). In coatings, Ag₂O nanoparticles can reduce bacterial adhesion and biofilm development on biomedical devices. In biosensors, their electrical and catalytic properties may contribute to signal enhancement, while their antimicrobial character may help reduce contamination of the sensing interface. Ag₂O nanoparticles also have potential in cancer-related biomedical studies because silver-based nanomaterials can induce oxidative stress, mitochondrial dysfunction, apoptosis, and cell-cycle changes. However, this area requires careful interpretation.

Cytotoxicity against cancer cells does not automatically indicate safe therapeutic selectivity. Any anticancer use would require detailed comparison between cancer cells and normal cells, dose-response analysis, mechanistic validation, and in vivo safety assessment. For this reason, in the context of Ag₂O/MXene nanocomposites, the strongest and most defensible biomedical focus remains antimicrobial wound healing and infection control, while cancer therapy should be discussed as an emerging secondary application (Alsaiani et al., 2023).

3.3 Cytotoxicity and biosafety concerns

Although Ag₂O nanoparticles are promising antimicrobial agents, cytotoxicity remains a central concern. Silver-based nanoparticles can affect mammalian cells through Ag⁺ release, ROS generation, mitochondrial dysfunction, membrane damage, inflammation, and DNA damage. A systematic review on silver nanoparticle-induced cytotoxicity reported that oxidative activity and silver-ion release can produce negative biological effects by inducing cytotoxicity (Chetry et al., 2025). Classic cytotoxicity studies on silver nanoparticles have proposed mechanisms involving mitochondrial respiratory-chain disruption, ROS production, ATP depletion, DNA damage, and cell-cycle arrest (Chery et al., 2025).

Although these findings are often based on AgNPs rather than Ag₂O specifically, they are highly relevant because Ag₂O nanoparticles can also act through silver-ion-related and oxidative-stress-related pathways. The cytotoxicity of Ag₂O nanoparticles depends on particle size, shape, surface charge, concentration, exposure duration, dissolution rate, and cell type. High concentrations may damage fibroblasts, keratinocytes, endothelial cells, immune cells, or other mammalian cells that are essential for tissue repair. This is particularly important in wound-healing applications because an antimicrobial material must kill bacteria without delaying cell migration, collagen deposition, angiogenesis, and re-epithelialization. Therefore, Ag₂O-based wound materials should be evaluated not only by antibacterial inhibition zones but also by cell viability, hemocompatibility, oxidative stress markers, inflammatory cytokines, and in vivo healing outcomes (Zia et al., 2025).

Surface modification is a major strategy to reduce cytotoxicity. Coating Ag₂O nanoparticles with biopolymers, proteins, plant-derived molecules, chitosan, alginate, polyethylene glycol, or hydrogel networks can moderate Ag⁺ release and reduce direct damage to mammalian cells. Similarly, loading Ag₂O nanoparticles onto Ti₃C₂T_x MXene may improve dispersion and enable controlled antibacterial action at lower silver doses. However, MXene itself

introduces additional safety questions, including oxidation, flake-size-dependent biological response, long-term persistence, and immune interactions. Thus, Ag₂O/MXene biomedical systems should be designed with careful attention to dose optimization, degradation behavior, and long-term biocompatibility (Yang et al., 2024).

3.4 MXenes in Biomedical Applications

MXenes are a rapidly expanding family of two-dimensional transition metal carbides, nitrides, and carbonitrides that have attracted considerable attention in biomedical research because of their unique combination of structural, electrical, chemical, optical, and surface properties. In comparison with many conventional nanomaterials, MXenes offer a distinctive layered architecture, high surface area, hydrophilic surface chemistry, excellent electrical conductivity, and strong light-to-heat conversion ability (Al Bsoul et al., 2019).

These characteristics make them promising materials for antibacterial therapy, wound healing, biosensing, drug delivery, photothermal cancer therapy, tissue engineering, and smart biomedical devices. Among the various MXenes reported so far, Ti₃C₂T_x MXene is the most widely investigated because it can be synthesized relatively easily from the Ti₃AlC₂ MAX phase, processed into nanosheets, chemically modified, and combined with polymers, metal nanoparticles, metal oxide nanoparticles, drugs, and biomolecules. Reviews describe MXenes as hydrophilic, conductive, tunable two-dimensional ceramic materials prepared by removing the “A” layer from MAX-phase precursors (Al Bsoul et al., 2019).

4. Structure of Ti₃C₂T_x MXene

Ti₃C₂T_x MXene has a layered two-dimensional structure composed of titanium and carbon atomic layers. It is commonly produced by selectively etching aluminum from the Ti₃AlC₂ MAX phase, followed by delamination or exfoliation to obtain few-layer or single-layer nanosheets. The general formula of MXenes is M_{n+1}X_nT_x, where M represents an early transition metal, X represents carbon and/or nitrogen, and T_x represents surface terminations generated during synthesis. In Ti₃C₂T_x, titanium acts as the transition metal component, carbon forms the carbide framework, and T_x represents terminal groups on the nanosheet surface. The two-dimensional morphology gives Ti₃C₂T_x a large surface-area-to-volume ratio, allowing extensive contact with bacteria, cells, biomolecules, drugs, polymers, and inorganic nanoparticles (Al Bsoul et al., 2019).

This structural feature is especially valuable for biomedical applications because it provides abundant active sites for loading antimicrobial agents, therapeutic molecules, or diagnostic components. The layered structure of Ti₃C₂T_x also makes it a suitable support for silver oxide nanoparticles. Ag₂O nanoparticles can be anchored or grown on the MXene surface, where the nanosheet acts as a scaffold that helps reduce nanoparticle aggregation and improves interfacial contact with microbial cells. In Ag₂O/MXene nanocomposites, the Ti₃C₂T_x sheet may therefore function not only as a carrier but also as an active antibacterial and photothermal component. This is important because free metal oxide nanoparticles often suffer from poor dispersion, uncontrolled release, and reduced effective surface area in biological environments (Al Bsoul et al., 2019).

4.1 Surface terminations and chemical reactivity

A defining feature of Ti₃C₂T_x MXene is the presence of surface functional groups. These surface terminations are commonly reported as –O, –OH, and –F, although other groups such as –Cl may appear depending on the synthesis method. The T_x groups are introduced during etching and post-treatment processes and strongly influence MXene properties, including hydrophilicity, surface charge, colloidal stability, oxidation behavior, conductivity, ion adsorption, drug loading, and biological interactions. ScienceDirect article previews describe T_x as surface functionalities such as –O, –OH, and –F, which depend on the etching agent used during MXene preparation (Abazari et al., 2026).

Surface terminations are particularly important in biomedical systems because they determine how MXenes interact with proteins, cells, bacteria, polymers, drugs, and nanoparticles. The oxygen- and hydroxyl-containing groups can promote hydrogen bonding, electrostatic interactions, and chemical coupling with biomolecules or polymer matrices. These groups also contribute to the hydrophilic character of Ti₃C₂T_x, allowing it to disperse more easily in aqueous media than many hydrophobic two-dimensional materials. In the context of Ag₂O/Ti₃C₂T_x nanocomposites, these functional groups can provide anchoring sites for silver oxide nanoparticle deposition, helping form more uniform hybrid structures (Abazari et al., 2026).

However, surface terminations may also introduce challenges. Fluorine-containing groups, depending on their

amount and stability, can affect biocompatibility and may require careful purification or replacement through surface modification. Oxidation of $\text{Ti}_3\text{C}_2\text{T}_x$ in water or physiological environments can also alter its surface chemistry and biological performance. Therefore, controlling the nature and density of surface terminations is essential for designing safe and reproducible MXene-based biomedical materials (Abdullah et al., 2025).

4.2 Hydrophilicity and aqueous dispersibility

One of the major advantages of $\text{Ti}_3\text{C}_2\text{T}_x$ MXene in biomedical research is its hydrophilicity. Unlike graphene and many other hydrophobic two-dimensional materials, $\text{Ti}_3\text{C}_2\text{T}_x$ can disperse relatively well in water because of its surface terminations. This property is highly beneficial for biomedical applications because most biological systems, including blood, wound fluid, cell-culture media, and physiological buffers, are aqueous environments. Hydrophilicity improves processability, supports interaction with hydrogels and polymers, and enables easier formulation into injectable systems, wound dressings, coatings, and biosensing platforms (Ahmed et al., 2015).

Hydrophilic $\text{Ti}_3\text{C}_2\text{T}_x$ nanosheets can be incorporated into natural and synthetic polymers such as chitosan, alginate, gelatin, cellulose, hyaluronic acid, polyethylene glycol, polyvinyl alcohol, and polyvinylpyrrolidone. Recent reviews on MXene-polymer biomedical nanocomposites note that such composites have been explored for photothermal cancer therapy, biosensors, antibacterial agents, bone regeneration, and targeted drug delivery. This compatibility with polymeric and biological matrices is especially important for wound-healing applications, where MXene-based materials may be integrated into hydrogels, membranes, sponges, or nanofiber scaffolds (Al-Azzani et al., 2025).

For $\text{Ag}_2\text{O}/\text{MXene}$ systems, hydrophilicity is important because it may improve the distribution of Ag_2O nanoparticles in aqueous formulations and reduce particle agglomeration. A well-dispersed $\text{Ag}_2\text{O}/\text{Ti}_3\text{C}_2\text{T}_x$ nanocomposite can provide more uniform antibacterial activity and better contact with bacteria than aggregated nanoparticles. In wound-dressing materials, hydrophilic MXene-based nanocomposites may also help maintain a moist wound environment, promote interaction with wound exudate, and support controlled release of active components (Al-Azzani et al., 2025).

4.3 Electrical conductivity and biosensing potential

$\text{Ti}_3\text{C}_2\text{T}_x$ MXene is also recognized for its excellent electrical conductivity. This property distinguishes MXenes from many conventional inorganic biomedical nanoparticles and makes them highly attractive for electrochemical biosensing, bioelectronic interfaces, wearable devices, and smart wound-monitoring systems (Wang et al., 2023). Conductive MXene nanosheets can facilitate electron transfer between biological analytes and electrode surfaces, improving signal sensitivity and response speed. This is useful for detecting biomarkers such as glucose, lactate, hydrogen peroxide, uric acid, inflammatory markers, bacterial metabolites, and wound-related biochemical signals (Wang et al., 2023).

The high conductivity of $\text{Ti}_3\text{C}_2\text{T}_x$ is also beneficial when MXene is combined with metal or metal oxide nanoparticles. In $\text{Ag}_2\text{O}/\text{Ti}_3\text{C}_2\text{T}_x$ nanocomposites, the conductive MXene framework may improve charge transfer and enhance electrochemical performance in biosensor applications. Silver oxide nanoparticles may contribute to catalytic or antimicrobial functions, while $\text{Ti}_3\text{C}_2\text{T}_x$ provides the conductive pathway and large active surface area. This combination is relevant for developing multifunctional biosensors that can both detect biological signals and resist microbial contamination (Wang et al., 2023).

Conductivity may also support electrically active wound dressings or tissue-engineering scaffolds. Electrical signals are involved in cell migration, tissue regeneration, and wound repair, and conductive materials can potentially support electroactive healing platforms. However, this field is still developing, and the biological effects of MXene conductivity must be carefully evaluated in relation to concentration, flake size, surface chemistry, and long-term stability (Wang et al., 2023).

4.4 Photothermal behavior

The strong photothermal behavior of $\text{Ti}_3\text{C}_2\text{T}_x$ MXene is one of its most important biomedical properties. $\text{Ti}_3\text{C}_2\text{T}_x$ absorbs near-infrared light and converts it into heat, enabling localized temperature elevation under external irradiation. This photothermal conversion is useful for cancer therapy, antibacterial treatment, controlled drug release, and wound-disinfection strategies. Surface-modified $\text{Ti}_3\text{C}_2\text{T}_x$ systems have been reported as promising platforms for near-infrared-triggered drug release and synergistic photothermal therapy (Ye et al., 2024).

In antibacterial applications, MXene-mediated photothermal heating can damage bacterial membranes, denature proteins, disrupt biofilms, and enhance the susceptibility of bacteria to antimicrobial agents. When combined with Ag₂O nanoparticles, photothermal heating may strengthen the antibacterial effect by increasing bacterial membrane permeability and improving the activity of Ag⁺ ions and ROS-mediated damage. This creates a potential synergistic mechanism in which MXene provides photothermal stress while Ag₂O contributes chemical antibacterial activity through silver ion release and oxidative stress. Photothermal behavior is also relevant to wound healing (Anwar et al., 2025).

MXene-containing hydrogels have been investigated for near-infrared-responsive antibacterial treatment and drug release. For example, a ciprofloxacin-loaded MXene/sodium alginate hydrogel was reported to show photothermal conversion capability under near-infrared irradiation, controlled drug release, antibacterial activity, and improved wound healing in experimental models. Such findings support the broader concept that MXene-based systems can be used as smart wound materials capable of combining antibacterial therapy with stimulus-responsive treatment (Anwar et al., 2025).

However, photothermal therapy must be carefully controlled. Excessive temperature can damage healthy tissue, delay healing, or cause inflammation. Therefore, MXene-based photothermal systems require optimization of laser power, irradiation time, material concentration, and tissue compatibility. In Ag₂O/MXene wound-healing systems, the goal should be moderate and localized heating that enhances antimicrobial activity without harming surrounding mammalian cells (Anwar et al., 2025).

4.5 Functionalization of Ti₃C₂T_x MXene

Functionalization is essential for translating Ti₃C₂T_x MXene into biomedical applications. Although pristine MXene possesses useful properties, surface modification is often needed to improve stability, reduce oxidation, enhance biocompatibility, control drug release, regulate biodistribution, and introduce targeting or antimicrobial functions. Functionalization can be achieved using polymers, biomolecules, drugs, metal nanoparticles, metal oxide nanoparticles, peptides, proteins, lipids, or hydrogel networks. ScienceDirect reports describe surface-modified MXenes as promising nanoplatforms for drug delivery because they offer high drug-loading capacity, multiple release modes, and biocompatibility, while polymer or nanoparticle modification can improve photothermal stability and biosafety (Mao et al., 2026).

Polymer functionalization is one of the most common strategies. Polyethylene glycol can improve colloidal stability and reduce nonspecific protein adsorption. Chitosan can add antimicrobial and wound-healing properties. Alginate and gelatin can support hydrogel formation and tissue compatibility. Hyaluronic acid can provide biological targeting and improved interaction with extracellular matrix components. These modifications can make MXene more suitable for wound dressings, injectable hydrogels, tissue scaffolds, and drug-delivery systems (Mao et al., 2026).

Inorganic functionalization is also important. Decorating Ti₃C₂T_x with Ag₂O nanoparticles can introduce strong antibacterial activity, while other nanoparticles such as Au, ZnO, TiO₂, Fe₃O₄, CuO, and CeO₂ may contribute catalytic, magnetic, antioxidant, or photothermal functions. For your review topic, Ag₂O functionalization is especially relevant because it may provide silver-ion release and ROS-mediated antibacterial activity while MXene improves dispersion, conductivity, and photothermal performance. The resulting Ag₂O/Ti₃C₂T_x nanocomposite can be discussed as a multifunctional biomedical platform rather than a simple physical mixture of two nanomaterials (Mao et al., 2026).

4.6 Biomedical applications of Ti₃C₂T_x MXene

Ti₃C₂T_x MXene has been studied in several biomedical areas. In antibacterial therapy, MXene nanosheets can interact with bacterial membranes, induce physical damage, generate oxidative stress, and enhance photothermal bacterial killing under near-infrared light. In wound healing, MXene-containing hydrogels and membranes may provide antibacterial protection, controlled drug release, photothermal disinfection, hemostatic support, and smart monitoring functions. In biosensing, MXenes' conductivity and large surface area allow sensitive electrochemical detection of biological molecules. In cancer therapy, MXene can serve as a photothermal agent and drug carrier, particularly when modified with polymers or nanoparticles. In tissue engineering, MXene can be incorporated into scaffolds to improve mechanical, electrical, and biological performance (Wang et al., 2024).

Despite these promising applications, MXene biomedical research still faces important limitations. These include oxidation instability, batch-to-batch variability, possible cytotoxicity, uncertain long-term biodegradation,

immune response, protein corona formation, and lack of standardized *in vivo* safety evaluation. Recent reviews emphasize that stability, biodegradation, protein corona formation, cell uptake, and immune interactions are key challenges for MXene-based biomedical translation. These concerns are particularly important when $\text{Ti}_3\text{C}_2\text{T}_x$ is combined with Ag_2O nanoparticles, because both components may influence oxidative stress, ion release, and cellular responses (Wang et al., 2023).

4.7 Antibacterial and wound-healing mechanisms

The antibacterial and wound-healing performance of $\text{Ag}_2\text{O}/\text{Ti}_3\text{C}_2\text{T}_x$ MXene nanocomposites can be understood as the result of multiple interacting mechanisms rather than a single mode of action (Figure 2). In this hybrid system, silver oxide nanoparticles mainly contribute chemical antibacterial activity through Ag^+ release, reactive oxygen species generation, and disruption of bacterial metabolism, while $\text{Ti}_3\text{C}_2\text{T}_x$ MXene provides a two-dimensional conductive and photothermal platform capable of membrane contact, physical bacterial damage, nanoparticle dispersion, and near-infrared-responsive antibacterial action (Li et al., 2025).

This multifunctional behavior is particularly important for infected wounds, where bacterial colonization, biofilm formation, oxidative imbalance, prolonged inflammation, and impaired tissue regeneration occur simultaneously. Recent reviews identify MXene antibacterial mechanisms as physical membrane damage, induced oxidative stress, and photothermal or photodynamic effects, while silver-based nanomaterials are widely associated with Ag^+ release, ROS formation, cell-wall disruption, and inhibition of bacterial biomolecules (Li et al., 2025).

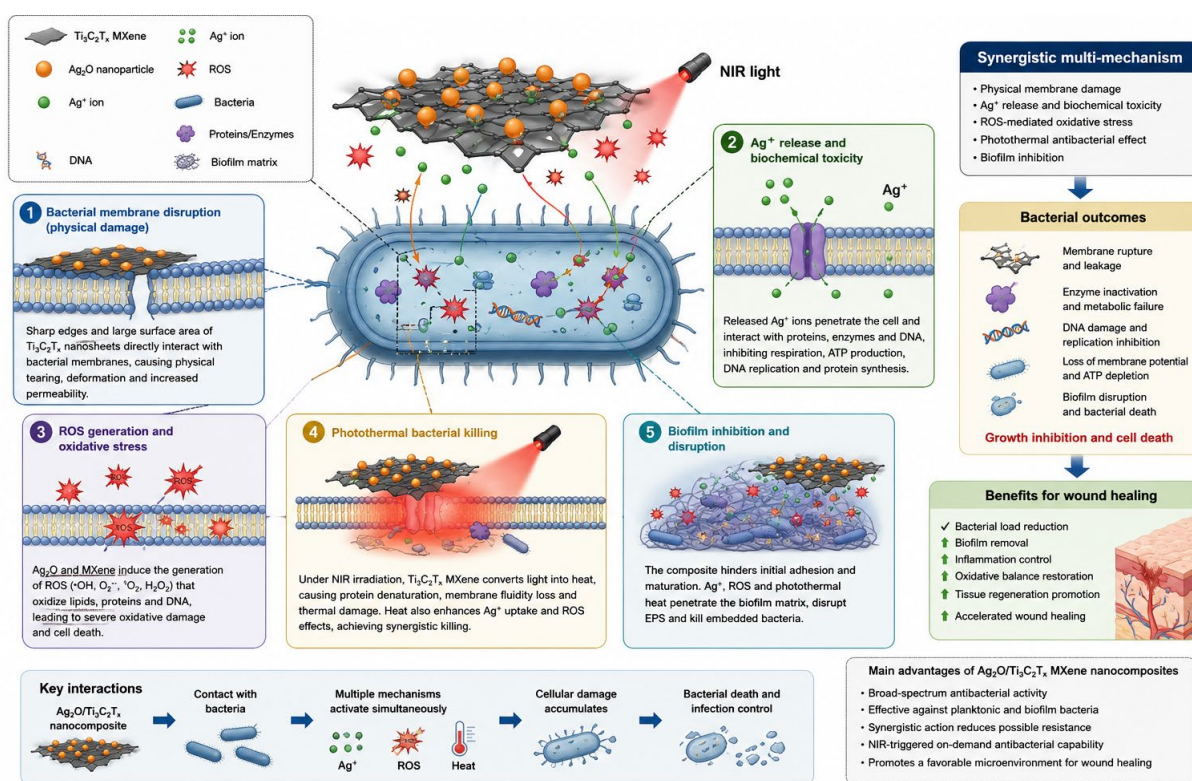


Figure 2. Schematic representation of the multifunctional antibacterial mechanism of $\text{Ag}_2\text{O}/\text{Ti}_3\text{C}_2\text{T}_x$ MXene nanocomposites. Source: Authors, 2026.

4.8 Bacterial membrane disruption

Bacterial membrane disruption is one of the primary antibacterial mechanisms expected in $\text{Ag}_2\text{O}/\text{Ti}_3\text{C}_2\text{T}_x$ MXene nanocomposites. Bacterial cell envelopes are essential for maintaining osmotic balance, nutrient transport, energy production, and protection from environmental stress. When this barrier is damaged, intracellular materials can leak out, membrane potential can collapse, and bacterial cells may lose viability. $\text{Ti}_3\text{C}_2\text{T}_x$ MXene contributes to this process through its two-dimensional nanosheet morphology (Zou et al., 2026).

The sharp edges and large surface area of MXene nanosheets can interact directly with bacterial membranes, producing a “nanoknife-like” physical effect that disrupts membrane integrity. The first widely cited study on $\text{Ti}_3\text{C}_2\text{T}_x$ MXene antibacterial activity reported that direct contact with MXene can damage bacterial membranes and lead to cell death. Ag_2O nanoparticles can strengthen this membrane-disruptive effect. Ag_2O particles or released Ag^+ ions can attach to bacterial cell walls and membranes through electrostatic interactions, especially because bacterial surfaces often contain negatively charged groups such as phosphate, carboxyl, and teichoic acid residues (Zou et al., 2026).

This interaction can increase membrane permeability, disturb membrane proteins, and promote leakage of cytoplasmic contents. In an Ag_2O /MXene hybrid, MXene may improve Ag_2O dispersion across a broad two-dimensional surface, increasing the probability that Ag_2O and Ag^+ species come into close contact with bacterial cells. Therefore, the membrane-disruptive mechanism is likely to involve both physical tearing or stress from $\text{Ti}_3\text{C}_2\text{T}_x$ nanosheets and biochemical membrane weakening by Ag_2O -derived silver species. The response may differ between Gram-positive and Gram-negative bacteria (Zou et al., 2026).

Gram-negative bacteria such as *E. coli* possess an outer membrane and a thin peptidoglycan layer, whereas Gram-positive bacteria such as *Staphylococcus aureus* contain a thicker peptidoglycan wall. These structural differences influence nanoparticle attachment, ion penetration, and susceptibility to oxidative damage. A recent study on biosynthesized Ag_2O nanoparticles reported antibacterial activity against both *S. aureus* and *E. coli*, supporting the relevance of Ag_2O nanoparticles for broad-spectrum antibacterial applications (Zou et al., 2026).

4.9 Ag^+ release and biochemical toxicity

Ag^+ release is a central mechanism in silver oxide nanoparticle antibacterial activity. In aqueous or biological environments, Ag_2O nanoparticles can act as a source of silver ions (Fan et al., 2025). These ions can interact with sulfur-, nitrogen-, oxygen-, and phosphorus-containing groups in proteins, enzymes, membrane components, and nucleic acids. As a result, Ag^+ can interfere with bacterial respiration, damage enzymes, inhibit ATP production, disturb DNA replication, and impair protein function. Silver nanoparticle reviews consistently describe Ag^+ release as a major contributor to antibacterial activity, along with membrane damage, ROS generation, and disruption of DNA and protein synthesis (Fan et al., 2025).

In $\text{Ag}_2\text{O}/\text{Ti}_3\text{C}_2\text{T}_x$ MXene nanocomposites, controlled Ag^+ release is especially important. A moderate and sustained release of Ag^+ may maintain antibacterial activity overtime, which is beneficial for wound dressings and antimicrobial coatings. However, excessive Ag^+ release may increase cytotoxicity toward mammalian cells such as fibroblasts, keratinocytes, and endothelial cells, which are essential for tissue repair. Therefore, the MXene surface can be considered a useful support for regulating Ag_2O distribution and reducing the need for high silver loading. If Ag_2O nanoparticles are uniformly anchored on $\text{Ti}_3\text{C}_2\text{T}_x$ nanosheets, the hybrid may achieve antibacterial efficiency at lower Ag_2O concentrations, potentially reducing host-cell toxicity. The Ag^+ release mechanism is also relevant to biofilm control (Fan et al., 2025; Tahi et al., 2021).

In biofilms, bacterial cells are protected by an extracellular polymeric matrix composed of polysaccharides, proteins, extracellular DNA, and lipids. Released Ag^+ ions may diffuse into this matrix and interfere with embedded bacterial cells. However, diffusion through mature biofilms can be limited, which is why combining Ag^+ release with MXene-based physical contact and photothermal heating may be more effective than using Ag_2O nanoparticles alone (Tahi et al., 2021).

4.10 ROS generation and oxidative stress

Reactive oxygen species generation is another important antibacterial mechanism in Ag_2O /MXene systems. ROS such as hydroxyl radicals, superoxide anions, singlet oxygen, and hydrogen peroxide can oxidize membrane lipids, damage proteins, disrupt DNA, and interfere with bacterial metabolic processes. Silver-based nanoparticles are known to induce oxidative stress in bacteria, and this oxidative damage often acts together with Ag^+ release and membrane disruption (Rzajj et al., 2022). Reviews on silver nanoparticle mechanisms report that bacterial killing involves oxidative stress, protein dysfunction, membrane damage, and DNA damage.

Ag_2O nanoparticles may generate ROS either directly through surface reactions or indirectly through Ag^+ -mediated disturbance of bacterial redox balance. Once ROS levels exceed the antioxidant capacity of bacterial cells, oxidative damage accumulates and results in cell death. In $\text{Ag}_2\text{O}/\text{Ti}_3\text{C}_2\text{T}_x$ MXene nanocomposites, ROS-mediated killing may be enhanced by intimate contact between the composite surface and the bacterial envelope. MXene’s large surface area may support the distribution of Ag_2O nanoparticles and increase local

oxidative stress at the bacteria–material interface (Amin et al., 2026).

However, ROS generation must be carefully balanced in wound-healing applications. While ROS can help kill bacteria, excessive ROS may damage host cells, degrade extracellular matrix components, and prolong inflammation. Chronic wounds already contain elevated oxidative stress, which can impair fibroblast migration, angiogenesis, and collagen deposition. Therefore, an ideal Ag₂O/MXene wound dressing should generate enough ROS to suppress bacteria but not so much that it damages the wound bed. This balance may be improved by controlling Ag₂O loading, modifying the MXene surface, embedding the composite in hydrogels, or using stimulus-responsive release strategies (Amin et al., 2026).

4.11 Photothermal bacterial killing

Ti₃C₂T_x MXene has strong near-infrared absorption and photothermal conversion ability, which makes it useful for light-triggered antibacterial treatment. Under near-infrared irradiation, MXene can convert absorbed light into localized heat. This heat can weaken bacterial membranes, denature proteins, disrupt biofilm matrices, and reduce bacterial viability. MXene antibacterial reviews describe photothermal therapy as one of the key strategies by which MXene-based materials can inhibit bacteria, especially when combined with physical damage and oxidative stress (Readdy et al., 2026).

In Ag₂O/Ti₃C₂T_x nanocomposites, photothermal heating may work synergistically with Ag₂O. Local heat can increase bacterial membrane permeability, making bacteria more vulnerable to Ag⁺ entry and ROS-mediated damage. It may also improve the penetration of antimicrobial agents into biofilms by loosening the extracellular polymeric matrix. Therefore, MXene-mediated photothermal therapy can convert Ag₂O/MXene from a passive antimicrobial material into an externally controlled antibacterial platform (Readdy et al., 2026).

This mechanism is especially relevant for infected wound dressings because near-infrared light can be applied locally to the wound area. MXene-based flexible wound materials have been reviewed as promising systems for infected wound detection and treatment because they combine photothermal conversion, conductivity, flexible structure, and antibacterial performance. Nevertheless, photothermal treatment must be optimized carefully. Excessive heat may injure healthy tissue, damage newly forming blood vessels, or delay re-epithelialization. For biomedical applications, the desired outcome is controlled mild-to-moderate heating that enhances bacterial killing without causing thermal injury to surrounding cells (Shah et al., 2024).

4.12 Biofilm inhibition

Biofilm formation is a major obstacle in wound healing because biofilms protect bacteria from antibiotics, immune cells, and antimicrobial materials. Infected wounds often contain biofilm-forming bacteria such as *S. aureus*, *Pseudomonas aeruginosa*, and *E. coli*. Once a biofilm develops, bacterial cells become embedded in a dense extracellular polymeric substance that reduces antimicrobial penetration and supports persistent inflammation [70]. Reviews on infected wound management note that biofilm extracellular matrices limit antibacterial agent access and contribute to refractory wound infections. Ag₂O/Ti₃C₂T_x MXene nanocomposites may inhibit biofilms at several stages. First, the surface of the composite may prevent early bacterial adhesion by damaging bacterial membranes and reducing initial colonization (Li et al., 2025).

Second, Ag⁺ release can suppress bacterial proliferation and interfere with enzymes and proteins required for biofilm maturation. Third, ROS generation can damage extracellular DNA, proteins, and polysaccharides in the biofilm matrix. Fourth, MXene-mediated photothermal heating may soften or disrupt the biofilm structure, allowing deeper penetration of Ag⁺ and ROS. This combination is important because mature biofilms are difficult to eliminate using a single antibacterial mechanism (Li et al., 2025).

MXene's two-dimensional morphology may also improve biofilm contact. Unlike freely dispersed nanoparticles that may aggregate, Ag₂O-decorated MXene sheets can provide a broad contact interface with bacterial colonies. If incorporated into a hydrogel or wound membrane, the composite may continuously interact with the wound surface, preventing bacterial recolonization. This property is valuable for chronic wounds, burns, diabetic ulcers, and surgical wounds, where long-term infection prevention is often required (Li et al., 2025).

4.13 Inflammation control

Inflammation is a necessary phase of wound healing, but prolonged inflammation can delay tissue repair. In infected wounds, bacterial toxins, biofilms, excessive neutrophil activity, and oxidative stress can maintain a

chronic inflammatory state (Bakhtiar et al., 2023). This persistent inflammation damages host tissue, increases protease activity, delays fibroblast migration, and prevents normal extracellular matrix formation. Therefore, an effective antimicrobial wound material should not only kill bacteria but also help shift the wound environment from prolonged inflammation toward tissue regeneration.

Silver-based nanoparticles may contribute to inflammation control by lowering bacterial burden and reducing infection-driven inflammatory stimuli. Recent reviews on silver nanoparticles in wound healing report that AgNPs may support wound repair through antibacterial, anti-inflammatory, antioxidant, and cell proliferation-promoting properties, including downregulation of pro-inflammatory cytokines such as TNF- α , IL-1 β , and IL-6 in some reported models. Although much of this evidence is based on AgNPs rather than Ag₂O specifically, it is relevant because Ag₂O nanoparticles share silver-ion-related biological mechanisms. MXene may also support inflammation control indirectly (Rehman et al., 2016).

By reducing bacterial load through membrane disruption and photothermal killing, MXene-based materials may decrease the inflammatory signals associated with infection. In addition, MXene-based wound dressings are being studied for smart wound management because they can combine antibacterial action, sensing, flexible contact, and tissue-supportive properties. However, the inflammatory response to Ag₂O/MXene composites must be investigated carefully. Both Ag⁺ release and MXene oxidation products could potentially trigger oxidative stress or immune reactions if not properly controlled. Thus, anti-inflammatory claims should be supported by cytokine analysis, macrophage-polarization studies, histology, and in vivo wound-healing models (Rehman et al., 2016).

4.14 Tissue regeneration and wound repair

The final goal of an Ag₂O/Ti₃C₂T_x MXene wound dressing is not only bacterial killing but also tissue regeneration. Normal wound healing involves hemostasis, inflammation, proliferation, and remodeling (Ali et al., 2026). During the proliferative phase, fibroblasts migrate into the wound bed, keratinocytes support re-epithelialization, endothelial cells form new blood vessels, and extracellular matrix components such as collagen are deposited. Infected wounds often fail to progress through these stages because bacteria and biofilms maintain inflammation and damage new tissue.

Ag₂O/MXene composites may support tissue regeneration mainly by creating a cleaner and more controlled wound microenvironment. By reducing bacterial burden and biofilm formation, the composite can decrease infection-related inflammation and allow fibroblasts, keratinocytes, and endothelial cells to function more effectively. Silver nanoparticle wound-healing reviews report that silver-based nanomaterials can contribute to wound repair through infection inhibition, inflammatory regulation, oxidative balance, and promotion of cellular repair processes. Ti₃C₂T_x MXene may add further regenerative advantages. Its conductivity may support bioelectrical signaling in wound environments, while its hydrophilic and flexible nature makes it suitable for incorporation into hydrogels, membranes, and wearable dressings (Yasmeen et al., 2019).

MXene-based flexible wound materials have been described as useful because they combine electrical conductivity, photothermal conversion, surface chemistry, and acceptable biocompatibility, and they may help with pathogen removal, physical protection, and wound closure. In addition, MXene-containing dressings can be designed to monitor wound biomarkers such as pH, temperature, enzymes, and oxidative stress, enabling smart wound management (Yasmeen et al., 2019).

For Ag₂O/Ti₃C₂T_x systems, the most promising regenerative format is likely a composite hydrogel or flexible membrane. A hydrogel matrix can keep the wound moist, absorb exudate, reduce mechanical irritation, and control Ag⁺ release. MXene can provide conductivity and photothermal responsiveness, while Ag₂O provides antibacterial activity. Together, these functions may promote re-epithelialization, granulation tissue formation, angiogenesis, and collagen deposition, provided that material concentration and photothermal exposure are optimized for safety (Hayat et al., 2022).

4.15 Synergistic mechanism in Ag₂O/Ti₃C₂T_x MXene nanocomposites

The key advantage of Ag₂O/Ti₃C₂T_x MXene nanocomposites is the possibility of synergistic antibacterial and wound-healing action. Ag₂O nanoparticles provide Ag⁺ release and ROS-mediated biochemical damage. Ti₃C₂T_x MXene provides physical membrane disruption, high surface-area support, conductivity, and photothermal killing. When combined, these mechanisms can act simultaneously: MXene sheets bring Ag₂O nanoparticles into close contact with bacteria, Ag⁺ ions disturb bacterial metabolism, ROS induces oxidative injury, and photothermal heating weakens membranes and biofilms (Yasmeen et al., 2019). This multi-target action may reduce the ability

of bacteria to survive through a single resistance pathway. In wound-healing applications, this synergy should be interpreted carefully.

Strong antibacterial activity is beneficial only if the material remains compatible with mammalian cells. Excessive Ag^+ release, uncontrolled ROS generation, high MXene concentration, or overheating during photothermal therapy may harm fibroblasts, keratinocytes, endothelial cells, and immune cells. Therefore, future $\text{Ag}_2\text{O}/\text{MXene}$ studies should evaluate antibacterial activity together with cytocompatibility, hemocompatibility, inflammatory markers, oxidative stress levels, angiogenesis, collagen deposition, and long-term tissue response. Overall, $\text{Ag}_2\text{O}/\text{Ti}_3\text{C}_2\text{T}_x$ MXene nanocomposites represent a promising multifunctional strategy for infected wound management because they combine bacterial membrane disruption, Ag^+ release, ROS generation, photothermal therapy, biofilm inhibition, inflammation regulation, and tissue-regenerative support in a single material platform (Zada et al., 2026).

5. Future Research Directions

Despite the remarkable advances achieved in $\text{Ag}_2\text{O}/\text{Ti}_3\text{C}_2\text{T}_x$ MXene nanocomposites, several scientific and technological challenges remain before these materials can be translated into routine clinical practice. Future research should move beyond improving antibacterial performance and focus on integrating advanced digital technologies, intelligent biomaterials, personalized therapeutic strategies, and scalable manufacturing processes. The convergence of nanotechnology, artificial intelligence (AI), and precision medicine is expected to transform the next generation of multifunctional biomedical platforms (Nguyen et al., 2024; Wang et al., 2025).

Artificial intelligence has emerged as a powerful tool for accelerating the design and optimization of advanced nanomaterials. Machine learning algorithms can analyze large experimental datasets to predict nanoparticle size, morphology, surface functionalization, colloidal stability, Ag^+ release kinetics, cytotoxicity, and antibacterial performance before laboratory synthesis. AI-assisted materials discovery can significantly reduce development time while identifying optimal combinations of MXene surface chemistry, Ag_2O loading, polymer composition, and photothermal properties. In addition, predictive computational models may facilitate the optimization of synthesis parameters, improving reproducibility and supporting large-scale manufacturing of $\text{Ag}_2\text{O}/\text{MXene}$ nanocomposites (Butler et al., 2018; Stach et al., 2021; Schleider et al., 2019).

Machine learning is also expected to play a central role in predicting biological responses to nanomaterials. By integrating physicochemical characteristics with biological datasets, predictive models can estimate cellular uptake, oxidative stress, inflammatory responses, biodistribution, biodegradation, and long-term biosafety. Such computational approaches may reduce experimental costs while improving the rational design of safer and more effective antibacterial nanocomposites. Furthermore, digital twin technologies combined with AI may eventually enable simulation of nanomaterial behavior in complex biological environments before *in vivo* validation (Moosaviet al., 2020; Wang et al., 2024).

Personalized medicine represents another promising direction for $\text{Ag}_2\text{O}/\text{Ti}_3\text{C}_2\text{T}_x$ MXene-based biomaterials. Future wound dressings may be customized according to individual patient characteristics, including age, immune status, microbial composition, diabetic condition, inflammatory profile, and wound microenvironment. AI-driven clinical decision systems could assist physicians in selecting the most appropriate nanocomposite formulation, silver concentration, photothermal irradiation parameters, and drug-loading strategy for each patient, thereby maximizing therapeutic efficacy while minimizing adverse effects (Topol, 2019; Xu et al., 2025).

The development of smart wound dressings is expected to become one of the most important biomedical applications of MXene-based nanocomposites. Future multifunctional dressings may combine antibacterial activity, photothermal therapy, controlled drug delivery, moisture regulation, electrical conductivity, and continuous monitoring of wound biomarkers such as pH, glucose, lactate, temperature, oxygen concentration, inflammatory cytokines, and reactive oxygen species. Real-time sensing capabilities could enable clinicians to monitor wound progression and rapidly detect infection or delayed healing without removing the dressing, thereby reducing patient discomfort and improving therapeutic outcomes (Deng et al., 2023; Mostafalu et al., 2018; Wang et al., 2025).

Wearable biosensors integrated with $\text{Ag}_2\text{O}/\text{Ti}_3\text{C}_2\text{T}_x$ MXene nanocomposites may further expand the clinical utility of these materials. Thanks to the exceptional electrical conductivity of $\text{Ti}_3\text{C}_2\text{T}_x$ MXene, flexible biosensors capable of continuously monitoring physiological signals and biochemical markers could be incorporated into intelligent wound dressings or wearable healthcare devices. Wireless data transmission to smartphones or cloud-based healthcare platforms would enable remote patient monitoring and facilitate early medical

intervention through telemedicine systems. Such digital healthcare technologies are expected to improve the management of chronic wounds, diabetic ulcers, burns, and post-surgical infections (Bandodkar; Wang, 2014; Heikenfeld et al., 2018; Ray et al., 2019).

Responsive biomaterials constitute another rapidly growing research field. Stimuli-responsive Ag₂O/MXene nanocomposites could intelligently regulate silver-ion release, photothermal activation, drug delivery, or antioxidant activity in response to environmental changes such as pH, temperature, bacterial enzymes, oxidative stress, electrical stimulation, or near-infrared irradiation. Such adaptive behavior would maximize antibacterial efficacy while reducing unnecessary exposure of healthy tissues to silver ions or excessive ROS generation. Future multifunctional hydrogels and nanocomposite membranes capable of self-regulating therapeutic activity may represent a significant advancement toward precision wound management (Ayed et al., 2026).

Finally, successful clinical translation will require multidisciplinary collaboration among materials scientists, microbiologists, biomedical engineers, clinicians, computational scientists, and regulatory agencies. Future investigations should prioritize standardized toxicity assessment, long-term biodegradation studies, scalable green synthesis, regulatory compliance, cost-effectiveness analyses, and well-designed preclinical and clinical studies. The integration of artificial intelligence, smart biomaterials, wearable electronics, and personalized medicine is expected to establish Ag₂O/Ti₃C₂T_x MXene nanocomposites as next-generation multifunctional platforms for precision antimicrobial therapy and advanced wound management.

6. Conclusions

Ag₂O/Ti₃C₂T_x MXene nanocomposites represent a promising emerging platform for biomedical applications, particularly in antibacterial wound healing, infection control, biofilm inhibition, and smart biomedical coatings. The integration of silver oxide nanoparticles with Ti₃C₂T_x MXene provides complementary properties that can enhance antimicrobial and therapeutic performance. Ag₂O nanoparticles contribute antibacterial activity through Ag⁺ release, reactive oxygen species generation, membrane disruption, and interference with bacterial metabolic processes. Ti₃C₂T_x MXene, on the other hand, offers a two-dimensional high-surface-area structure, hydrophilic surface terminations, excellent conductivity, photothermal conversion ability, and strong functionalization potential.

The combination of these two materials may create a synergistic biomedical system capable of bacterial killing, biofilm suppression, controlled therapeutic response, and support for tissue regeneration. In wound-healing applications, Ag₂O/MXene nanocomposites may help reduce microbial burden, limit infection-related inflammation, and provide a multifunctional platform for advanced antimicrobial dressings. However, despite their remarkable potential, these nanocomposites remain at an early stage of biomedical development. Their successful translation will require precise control over synthesis methods, Ag₂O loading, MXene oxidation stability, silver-ion release kinetics, long-term biocompatibility, biodegradation, and biosafety.

Future research should prioritize standardized synthesis protocols, scalable and cost-effective manufacturing strategies, reproducible physicochemical characterization, and comprehensive in vivo investigations to establish pharmacokinetics, immunological responses, long-term toxicity, and environmental safety. Particular attention should also be given to understanding the interactions between Ag₂O/MXene nanocomposites and complex biological systems, enabling rational material design for specific clinical applications.

From a translational perspective, major challenges include regulatory approval, large-scale production under good manufacturing practices, long-term storage stability, sterilization compatibility, and integration into clinically relevant formulations such as wound dressings, implant coatings, hydrogels, and drug-delivery systems. Addressing these barriers will be essential for bridging the gap between laboratory research and clinical implementation.

Overall, Ag₂O/Ti₃C₂T_x MXene nanocomposites represent one of the most promising next-generation multifunctional nanoplatforms for antimicrobial and regenerative medicine. Continued advances in materials engineering, nanotoxicology, biomedical validation, and industrial-scale fabrication are expected to accelerate their transition from experimental systems to clinically and commercially viable biomedical technologies, opening new opportunities for combating antimicrobial resistance and improving patient care.

7. Future Perspectives

Future research on Ag₂O/Ti₃C₂T_x MXene nanocomposites should focus on overcoming the major barriers that

currently limit their biomedical translation. One of the most important needs is the standardization of synthesis and characterization methods. Variations in MXene etching, delamination, surface terminations, Ag₂O nanoparticle size, Ag₂O loading, and synthesis conditions can strongly affect antibacterial activity, cytotoxicity, stability, and reproducibility. Therefore, future studies should establish clear and repeatable protocols for synthesis, purification, storage, and physicochemical characterization.

Material stability is another key area for future improvement. Ti₃C₂T_x MXene can undergo oxidation in aqueous and physiological environments, which may reduce its conductivity, photothermal efficiency, and biological performance. Similarly, uncontrolled Ag⁺ release from Ag₂O nanoparticles may increase toxicity toward mammalian cells. Future work should focus on improving oxidation resistance, controlling silver-ion release, and using protective strategies such as polymer coating, hydrogel encapsulation, biopolymer functionalization, and surface modification.

Scalable synthesis will also be essential for practical application. Most Ag₂O/MXene nanocomposites are currently prepared at the laboratory scale, and many reported methods are not suitable for large-scale production. Future studies should develop simple, cost-effective, reproducible, and environmentally friendly synthesis routes. In situ growth of Ag₂O nanoparticles on MXene nanosheets may be especially useful because it can improve nanoparticle dispersion, reduce aggregation, and enhance interfacial contact between Ag₂O and MXene.

In vivo validation is another critical requirement. In vitro antibacterial and cytotoxicity tests provide useful preliminary evidence, but they cannot fully represent the complexity of infected wounds and biological tissues. Future studies should include animal models of infected wounds, diabetic wounds, burn wounds, and biofilm-associated infections. Important biological parameters such as wound closure rate, bacterial load, inflammatory cytokines, oxidative stress, angiogenesis, collagen deposition, re-epithelialization, hemocompatibility, immune response, and long-term tissue safety should be evaluated.

Regulatory considerations should also be addressed early in the development process. Ag₂O/MXene-based wound dressings or biomedical coatings may be classified as nanomaterial-containing medical devices or combination products, depending on their composition and intended use. Therefore, future research should follow standardized biocompatibility, toxicity, sterilization, degradation, and safety-testing requirements. Long-term biosafety studies are particularly important because both Ag₂O nanoparticles and MXenes may influence oxidative stress, immune response, and cellular behavior.

Future studies should also compare Ag₂O/MXene systems with other metal oxide/MXene nanocomposites, including ZnO/MXene, CuO/MXene, TiO₂/MXene, and Fe₃O₄/MXene systems. Ag₂O/MXene may provide stronger antibacterial activity due to Ag⁺ release, while ZnO/MXene may offer low-cost antimicrobial and wound-healing potential. CuO/MXene may support antibacterial activity and angiogenesis-related repair, TiO₂/MXene may provide better chemical stability and photocatalytic behavior, and Fe₃O₄/MXene may offer magnetic responsiveness for targeted therapy or imaging. Comparative studies under identical experimental conditions will be necessary to determine which nanocomposite is most suitable for specific biomedical applications.

Overall, the future success of Ag₂O/Ti₃C₂T_x MXene nanocomposites will depend on rational material design, standardized testing, scalable fabrication, surface engineering, and detailed in vivo validation. If these challenges are addressed, Ag₂O/MXene-based materials could become valuable candidates for advanced wound dressings, antimicrobial coatings, biosensors, and smart biomedical platforms.

8. Authors' Contributions

Hifsa Nawaz: contributed to the conceptualization, literature review, data collection, manuscript preparation, and critical revision of the article. *Osama Ali Khattak*: contributed to the study design, supervision, validation, review, and editing of the manuscript. Both authors read and approved the final version of the manuscript.

9. Conflicts of Interest

No conflicts of interest.

10. Ethics Approval

Not applicable.

11. Artificial Intelligence Statement: Declaration of Generative AI and AI-Assisted Technologies in the Writing Process

The authors declare that generative artificial intelligence (AI) was used exclusively for the creation of figures, illustrations, and the Graphical Abstract included in this manuscript. No AI tools were used to generate, interpret, analyze, or modify the scientific content, results, discussion, or conclusions of the study. All AI-generated visual materials were carefully reviewed, verified, and approved by the authors, who assume full responsibility for their accuracy, originality, and compliance with the scientific content of the manuscript. The use of AI is disclosed in the corresponding figure legends (or captions), including the name of the AI tool, model, or version (when available), and the year of use. AI tools are not recognized as authors and do not assume responsibility or accountability for the content of this manuscript.

12. References

- Abazari, M., Akbari, T., Badeleh, S. M., Hasani, M., Foroumadi, A., Sharifikolouei, E., & Khoobi, M. (2026). A comprehensive review on the hemostatic properties of metal-based materials and substances. *Biological Trace Element Research*, 204, 4631-4655. <https://doi.org/10.1007/s12011-026-04985-y>
- Abdullah, W., Ab Razak, N. N. A. N., Dheyab, M. A., Salem, F., Aziz, A. A., & Ghasemlou M. (2025). Melanin-driven green synthesis and surface modification of metal and metal-oxide nanoparticles for biomedical applications. *Advanced Functional Materials*, 35(43), 2503017. <https://doi.org/10.1002/adfm.202503017>
- Ahmad, S., Akhtar, N., Fazil, P., Ahamd, M. S., Khan, J. A., Mirza, S., Qarni, A., Irfan, S., & Ateeq, M. (2026). Visible-light-active magnetic CuFe₂O₄ and Fe₃O₄ nanoparticles: efficient photocatalysts for allura red dye degradation with enhanced antibacterial activity. *ChemistrySelect*, 11(16), e05042. <https://doi.org/10.1002/slct.202505042>
- Ahmed, I., Shah, S., Ayaz, M., Ahmed, I., Ali, M., Ahmad, N., & Ahmad, I. (2015). Production of biodiesel from algae. *Journal of Pure and Applied Microbiology*, 9(1), 79-85.
- Al Bsoul, A., Hailat, M., Abdelhay, A., Tawalbeh, M., Jum'ah, I., & Bani-Melhem, K. (2019). Treatment of olive mill effluent by adsorption on titanium oxide nanoparticles. *Science of the Total Environment*, 688, 1327-1334. <https://doi.org/10.1016/j.scitotenv.2019.06.381>
- Al-Azzani, H., Vithran, D. T. A., Aliouat, H., Zhou, W., & Mao, X. (2025). Precision bacterial immunotherapy: an integrated mechanistic taxonomy and translational roadmap against antimicrobial resistance. *Frontiers in Immunology*, 16, 1675682. <https://doi.org/10.3389/fimmu.2025.1675682>
- Ali, A., Khan, S. R., Shah, M., Matsumoto, M., Tahara, Y., Muhammad, S., & Khan, S. (2025). Fabrication, characterization, and adsorption studies of thermally modified peanut shell charcoal for Orange G dye removal. *Biomass Conversion and Biorefinery*, 15(10), 15645-15653. <https://doi.org/10.1007/s13399-024-06451-y>
- Ali, S., Ali, S., Ismail, A., Wang, Y., Rahim, S., Raziq, F., & Qiao, L. (2026). Defective CeO₂/copper phthalocyanine S-scheme heterojunctions with molecular copper centers for selective CO₂-To-CO photoconversion. *Electron*, e70050. <https://doi.org/10.1002/elt2.70050>
- Alsaiani, M., Roghani, K., Liaqat, S., Alkorbi, A. S., Sharif, F., Irfan, M., & Ahmad, N. (2023). Effect of ionic liquids on mechanical, physical, and antifungal properties and biocompatibility of a soft denture lining material. *ACS Omega*, 8(30), 27300-27311. <https://doi.org/10.1021/acsomega.3c02677>
- Amin, M., Abbas, M. A., Mahar, J., Shahzad, M. S., & Rasool, M. S. (2026). Phyto-mediated green synthesis and physicochemical characterization of titanium dioxide nanoparticles for environmental and pharmacological applications. *Journal of Physical and Chemical Studies*, 1(4), 17-56. <https://doi.org/10.5281/zenodo.19767807>
- Amir, J., Muhammad, S., Kashif, M., Khan, A. A., Gul, M., Sun, H., Azizi, S., & Maaza, M. (2025). Synthesis, characterization and dielectric properties evaluation of NiO-Co₃O₄ nanocomposite. *Journal of the Iranian Chemical Society*, 22(1), 63-72.
- Anwar, N., Shah, M., Anwar, S. H., Shah, M. I. A., Zada, A., & Abd-Allah, E. F. (2025). Bio-catalytic activity of novel poly (ethylene glycol) methacrylate hybridized silver nanomaterials. *South African Journal of Botany*,

- 176, 197-206. <https://doi.org/10.1016/j.sajb.2024.11.017>
- Ayed, A. B., Masoudi, M., & Namvari, M. (2026). Engineered 3D MXene- and GO-based Ag nanocomposites with enhanced stability and antibacterial performance. *FlatChem*, 57, 101052. <https://doi.org/10.1016/j.flatc.2026.101052>
- Azam, J., Ahmad, Z., Irfan, A., Naz, A., Arshad, M., Sattar, R., Raish, M., Abbasi, B. B. K., & Hardan, Y. A. B. (2025). Polyol formation of silver@metal oxides nanohybrid for photocatalytic and antibacterial performance. *Catalysts*, 15(3), 283. <https://doi.org/10.3390/catal15030283>
- Bakhtiar, S. U. H., Zada, A., Raziq, F., Ali, S., Khan, W., Nazir, R., Dong, W., & Fu, Q. (2023). Zinc phthalocyanine sensitized g-C₃N₄ photocatalyst for exceptional photocatalytic hydrogen evolution and pollutant degradation. *International Journal of Hydrogen Energy*, 48(43), 16320-16329. <https://doi.org/10.1016/j.ijhydene.2023.01.152>
- Bandodkar, A. J., & Wang, J. (2014). Non-invasive wearable electrochemical sensors. *Trends in Biotechnology*, 32(7), 363-371. <https://doi.org/10.1016/j.tibtech.2014.04.005>
- Bushra, Kashif, M., Khairullah, Khan, A. A., Sun, H., Yousaf, J., Shah, M. I. A., Hussain, S., Amir, J., Jamal, Y., & Ahmad, T. (2024b). Synthesis and characterization of Fe-doped CuO nanoparticles: Catalytic efficiency in crystal violet dye degradation and exploration of electrical properties. *Brazilian Journal of Science*, 3(8), 1-18. <https://doi.org/10.14295/bjs.v3i8.601>
- Butler, J., Handy, E. D., Upton, M., & Besinis, A. (2023). Review of antimicrobial nanocatings in medicine and dentistry: Mechanisms of action, biocompatibility performance, safety, and benefits compared to antibiotics. *ACS Nano*, 17(8), 7064-7092. <https://doi.org/10.1021/acsnano.2c12488>
- Butler, K. T., Davies, D. W., Cartwright, H., Isayev, O., & Walsh, A. (2018). Machine learning for molecular and materials science. *Nature*, 559, 547-555. <https://doi.org/10.1038/s41586-018-0337-2>
- Chetry, M., Feng, R., Babar, S., Sun, H., Zafar, I., Mohany, M., Afridi, H. I., Khan, N. U., Ali, I., Shafiq, M., & Khan, S. (2025). Early detection and analysis of accurate breast cancer for improved diagnosis using deep supervised learning for enhanced patient outcomes. *Peer J Computer Science*, 11, e2784. <https://doi.org/10.7717/peerj-cs.2784>
- Del Toro, F., Mencía, E., Vallarino, J. G., Makki, M., Sun, H., & Canto, T. (2024). A potato virus Y infection under ambient conditions that turn it asymptomatic affects the physiology of the host, and its interplay with drought. *Preprints.org*. <http://doi.org/10.20944/preprints202407.1421.v1>
- Del Toro, F., Sun, H., Robinson, C., Jiménez, Á., Coviellas, E., Higuera, T., Aguilar, E., Tenllado, F., & Canto, T. (2022). *In planta* vs viral expression of HCPro affects its binding of nonplant 21-22-nucleotide small RNAs, but not its preference for 5'-terminal adenines or its effects on small RNA methylation. *New Phytologist*, 233(5), 2266-2281. <https://doi.org/10.1111/nph.17935>
- Deng, Z., Xiang, Z., Zhu, S., Zhang, Y., Du, Y., Wang, S., Kang, Z., Wang, Z., Tong, X., & Liu, Y. (2025). Switching cathodic/anodic electrochemiluminescence of Ru (bpy)₃²⁺ Precisely via homogeneous nickel nanoparticles crystal facets sites modulated ORR/OER. *Exploration*, 5(5), 20250036. <https://doi.org/10.1002/EXP.20250036>
- Elahi, N., & Rizwan, M. (2021). Progress and prospects of magnetic iron oxide nanoparticles in biomedical applications: A review. *Artificial Organs*, 45(11), 1272-1299. <https://doi.org/10.1111/aor.14027>
- European Medicines Agency. (EMA). (2024). Medical devices and nanotechnology. Available in: <https://www.ema.europa.eu>. Accessed on: July 10, 2026.
- Fan, Z., Gao, F., Zhang, J., Luo, N., Yi, H., & Tang, X. (2025). Advances in CO catalytic oxidation on typical metal oxide catalysts: performance, mechanism, and optimization. *Journal of Materials Chemistry A*, 13(32), 26129-26165. <https://doi.org/10.1039/d5ta03067f>
- Ghani, I., Kashif, M., Khattak, O. A., Shah, M., Nawaz, S., Ullah, S., Murad, S., Naz, S., Khan, H. W., Muhammad, S., & Jamal, M. (2023). Hydrothermal synthesis and characterization of Cobalt doped Bismuth oxide NPs for photocatalytic degradation of methyl orange dye. *Journal of Xi'an Shiyu University, Natural Science Edition*, 19(7), 1195-1217.
- Gul, M., Kashif, M., Muhammad, S., Azizi, S., & Sun, H. (2025). Various methods of synthesis and applications of gold-based nanomaterials: a detailed review. *Crystal Growth & Design*, 25(7), 2227-2266. <https://doi.org/10.1021/acs.cgd.4c01687>

- Gul, M., Kashif, M., Shahid, K., & Natasha. (2024). Eco-friendly approaches in the synthesis of ZnO nanoparticles using plant extract: A review. *Phytopharmacology Research Journal*, 3(2), 1-25.
- Hao, S., Han, H., Yang, Z., Chen, M., Jiang, Y., Lu, G., Dong, L., Wen, H., Li, H., Liu, J., Wu, L., Wang, Z., & Wang, F. (2022). Recent advancements on photothermal conversion and antibacterial applications over MXenes-based materials. *Nano-Micro Letters*, 14. <https://doi.org/10.1007/s40820-022-00901-w>
- Harun-Ur-Rashid, M., Foyez, T., Krishna, S. B. N., Poda, S., & Imran, A. B. (2025). Recent advances of silver nanoparticle-based polymer nanocomposites for biomedical applications. *Royal Society of Chemistry*, 15(11), 8480-8505. <https://doi.org/10.1039/d4ra08220f>
- Hayat, A., Sohail, M., Hamdy, M. S., Mane, S. K. B., Amin, M. A., Zada, A., Medina, D. I., & Nawawi, W. I. (2022). Biomass lignin integrated polymeric carbon nitride for boosted photocatalytic hydrogen and oxygen evolution reactions. *Molecular Analysis*, 518, 112064. <https://doi.org/10.1016/j.mcat.2021.112064>
- Heikenfeld, J., Jajack, A., Rogers, J., Tian, L., Khine, M., & Wang, J. (2018). Wearable sensors: Modalities, challenges and prospects. *Lab on a Chip*, 18, 217-248. <https://doi.org/10.1039/C7LC00914C>
- Hussain, S., Kashif, M., Ali, M., Gul, M., Azizi, S., & Maaza, M. (2026). Ligand-engineered mesoporous silica: Cutting-edge architectures for targeted toxic heavy metal sequestration – A review. *Advanced Materials Science and Engineering*, 2026(1), 3228002. <https://doi.org/10.1155/amse/3228002>
- Irfan, S., Ali, H., Aman, N., Gao, C., Qiao, Z., Sun, H., Amir, J., Shah, A., & Kashif, M. (2024). Biomedical Applications of Titanium Dioxide (TiO₂) Nanoparticles. *Phytopharmacology Research Journal*, 3(3), 29-40.
- Jamal, M., Nabi, G. A. K., Sun, H., Ullah, K., Khattak, O. A., Kashif, M., Khan, S., Alam, M., Hussain, S., Ullah, M., Aleena, S., Haq, H., Umar, S., Atif, M., Hussain, I., & Masood, A. (2024). Preparation of manganese-doped bismuth oxide for the photocatalytic degradation of methylene blue. *Archives of Advanced Engineering Science*, 1-7. <https://doi.org/10.47852/bonviewAAES42023402>
- Jamil, M., Shah, A., Aman, G., Shabir, F., Begum, R., Sun, H., Rafiq, S., Iqbal, N., Aman, N., Aman, N., & Liaqat, Z. (2025). Bismuth vanadate nanoparticles: Structure, synthesis, and emerging engineering applications. *Biomedical: Journal of Scientific & Technical Research*, 62(3), 54728-54740. <https://dx.doi.org/10.26717/BJSTR.2025.62.009758>
- Jangra, S., Kumar, B., Sharma, J., Das, S., & Goyat, M. S. (2025). MXenes: synthesis, properties, and applications in advanced energy storage technologies. *Zastita Materijala*, 66(3). <https://doi.org/10.62638/ZasMat1216>
- Jia, B., et al., Zhao, L., Tang, M., Xie, N., Huang, Y., Liang, X., Yang, G., Wu, Q., & Sun, Z. (2026). Neuron–tumor crosstalk in cancer: molecular mechanisms and translational advances. *Molecular Cancer*. <https://doi.org/10.1186/s12943-026-02715-5>
- Kashif, M., Gul, M., Shahzad, N., Sun, H., Shezan, A. A., Ahmad, N., Hamkoui, O., & Tozan, H. (2026). Metal oxide nanoparticles: A comprehensive review of recent advances in synthesis strategies, characterization and multifunctional applications. *Preprints.org* 10. <https://www.preprints.org/manuscript/202606.1716>
- Kashif, M., Jawad, M., Khan, A. A., Sun, H., Ullah, K., Fakayode, O. J., & Azizi, S. (2024a). Fe/Ti-codoped strontium oxide nanoparticles for enhanced photocatalytic degradation of methyl orange. *Journal of Applied Research in Water and Wastewater*, 11(1), 8-14. <https://doi.org/10.22126/arww.2024.10753.1336>
- Kashif, M., Sharif, T., Khan, S., Shahzad, N., Amir, J., Gul, M., Shahid, K., Qarni, A., Shah, A., & Matinise, N. (2026). Synthesis strategies and multifaceted applications of molybdenum - based nanomaterials: A comprehensive review. *Scientifica*, 2026(1), 1764400. <https://doi.org/10.1155/sci5/1764400>
- Khan, M., Sun, X., Kashif, M., Zada, A., Azizi, S., Ragab, A. H., Taher, M. A., Abbas, Q., & Shehzad, K. (2025). Exploration of bismuth-based nanomaterials: From fundamental concepts to innovative synthesis techniques and emerging applications. *Coordination Chemistry Reviews*, 538, 216687. <https://doi.org/10.1016/j.ccr.2025.216687>
- Khan, S., Kalsoom, U., Jashif, M., Hussain, S. A., Gul, M., Azizi, S., & Maaza, M. (2025). Smart and sustainable microplastic removal: Hybrid systems, bio-inspired technologies, real-time sensing, and policy integration. *Water, Air, & Soil Pollution*, 236(14), 900. <https://doi.org/10.1007/s11270-025-08468-z>
- Li, J., Zhang, Y., Han, Y., Chen, J., Zada, A., Han, Y., Li, X., & Dang, A. (2026). In-situ construction of Ni on fix-reduced graphene fibers by electroless plating strategy for extraordinary electromagnetic wave adsorption. *Colloids and Surfaces A: Physicochemical and Engineering*, 139083.

<https://doi.org/10.1016/j.colsurfa.2025.139083>

- Li, L., Mansor, Z., Ismail, F. F., Zhao, X., Guo, X., Sun, H., Jing, Y., & Xu, Y. (2025). Compliance-aware and explainable GA-optimized neural network for cost estimation in safety-critical medical software. *Research Square*. <https://doi.org/10.21203/rs.3.rs-7593580/v1>
- Li, L., Mansor, Z., Ismail, F. F., Zhao, X., Li, X., Sun, H., & Guo, X. (2026). Explainable AI-driven optimization for transparent and auditable decision-making in medical software. *Journal of King Saud University Computer and Information Sciences*. <https://doi.org/10.1007/s44443-026-00748-w>
- Li, L., Mansor, Z., Zhao, X., Xiong, X., Guo, X., Li, X., & Sun, H. (2026). An explainable hyperparameter-optimized genetic algorithm-backpropagation (GA-BP) neural network model for medical software cost estimation. *PeerJ Computer Science*, 12, e3477. <https://doi.org/10.7717/peerj-cs.3477>
- Li, Z., Sun, H., Chen, X., Peng, P., Sun, H., Chen, S., Hashif, M., Xie, R., Liang, Q., Luo, Y., Li, T., Ou, Q., Huang, S., & Jiang, C. (2025). Integrated multiomics elucidates glutathione metabolic regulation in a marine aromatic probiotic yeast *Meyerozyma guilliermondii* GXDK6 under salt stress. *ACS Omega*, 10(41), 48965-48975. <https://doi.org/10.1021/acsomega.5c07376>
- Madani, S. S., Habibi-Yangjeh, A., Asadzadeh-Khaneghah, S., Chand, H., Krishnan, V., & Zada, A. (2021). Integration of Bi₄O₅I₂ nanoparticles with ZnO: impressive visible-light-induced systems for elimination of aqueous contaminants. *Journal of the Taiwan Institute of Chemical Engineers*, 119, 177-186. <https://doi.org/10.1016/j.jtice.2021.01.020>
- Mao, Z., Liu, S., Lin, S., Qi, K., Zada, A., & Chai, S-P. (2026). Photocatalytic degradation of tetracycline and antibacterial performance by S-scheme Bi₂WO₆/TiO₂ heterojunction. *Chemical Research in Chinese Universities*, 42, 907-917. <https://doi.org/10.1007/s40242-026-5284-0>
- Moosavi, S. M., Nandy, A., Jablonka, K. M., Ongari, D., Janet, J. P., & Kulik, H. J. (2020). Understanding the diversity of the metal-organic framework ecosystem. *Nature Communications*, 11, 4068. <https://doi.org/10.1038/s41467-020-17755-8>
- Mostafalu, P., Rahimi, R., Ochoa, M., Khalilpour, A., Dokmeci, M. R., & Ziaie, B. (2018). A textile dressing for real-time sensing and treatment of chronic wounds. *Small*, 14, 1703509. <https://doi.org/10.1002/sml.201703509>
- Muhammad, S., Ali, A., Shah, J., Hamza, M., Kashif, M., Khel, B. K., & Iqbal, A. (2023). Using Moringa oleifera stem extract for green synthesis, characterization, and anti-inflammatory activity of silver oxide nanoparticles. *Natural and Applied Sciences International Journal*, 4(1), 80-97. <https://doi.org/10.47264/idea.nasij/4.1.6>
- Muhammad, S., Sun, H., Zahoor, S., Kahn, S., Ullah, R., Fu, B., Ullah, S., Isimjan, T. T., Azizi, S., & Yang, X. (2026). Advancing MOFs for electrocatalytic ORR, UOR, and CO₂RR: From fundamentals to device integration and deployment challenges. *Materials Science and Engineering: R: Reports*, 171, 101248.
- Muhammad, S., Wang, L., Gao, M., Khan, S., Xu, W., Ali, A., Isimjan, T. T., Azizi, S., & Yang, X. (2026). Fe-Ce interaction-driven active site modulation in a porous MOF for oxygen evolution reaction. *Fuel*, 405, 136782. <https://doi.org/10.1016/j.fuel.2025.136782>
- Muhammad, S., Wang, L., Huang, Z., Zhou, A., Bilal, H., Isimjan, T. T., & Yang, X. (2025). Recent advances in lanthanide-based materials for oxygen evolution reaction: Challenges and future prospects. *Coordination Chemistry Reviews*, 534, 216573. <https://doi.org/10.1016/j.ccr.2025.216573>
- Muhammad, S., Yao, B., Zhou, A., Huang, Z., Khan, S., Wei, F., Luo, Z., Isimjan, T. T., & Yang, X. (2025). Unveiling dynamic surface transformations: Mo-doped Fe-based MOFs as next-generation oxygen evolution catalysts. *Green Chemistry*, 27(19), 5554-5566.
- Ray, T. R., Choi, J., Bhandodkar, A. J., Tian, L., & Rogers, J. A. (2019). Bio-integrated wearable systems: A comprehensive review. *Chemical Reviews*, 119(8), 5461-5533. <https://doi.org/10.1021/acs.chemrev.8b00573>
- Reddy, S. S., Iqbal, A., Mayekar, J., Momin, N., & Radha, S. (2026). Nanostructured metal and metal oxide materials for advanced water filtration: Recent progress and perspectives. *International Journal of Research and Analytical Reviews*, 13(1).
- Rehman, A. U., Humayun, M., Khan, A., Zada, A., & Jing, L. (2016). Effect of biocides on the precipitation of calcium fluoride in the presence of anionic copolymeric inhibitors. *Toxicological & Environmental*

- Chemistry, 98(7), 748-758. <https://doi.org/10.1080/02772248.2015.1124107>
- Rzaij, J. M., Nawaf, S. O., & Ibrahim, A. K. (2022). A review on tin dioxide gas sensor: The role of the metal oxide doping, nanoparticles, and operating temperatures. *World Journal of Advanced Research and Reviews*, 14(01), 051. <https://doi.org/10.30574/wjarr.2022.14.1.0288>
- Schleder, G. R., Padilha, A. C. M., Acosta, C. M., Costa, M., & Fazzio, A. (2019). From DFT to machine learning: Recent approaches to materials science. *Journal of Physics: Materials*, 2, 032001. <https://doi.org/10.1088/2515-7639/ab084b>
- Shah, A., Sun, H., Qiao, Z., Khan, M. U., Ali, N., Amir, J., Aleena, S., & Kashif, M. (2024). Synthesis of iron oxide nanoparticles and its antimicrobial, anticancer, anti-inflammatory, wound healing, and immunomodulatory activities-A Review. *Phytopharmacology Research Journal*, 3(3), 1-28.
- Shah, J., Sun, H., Qiao, Z., Sharif, T., & Gul, M. (2024). Enhanced degradation of methylene blue dye using hydrothermally synthesized Nickel-doped Strontium oxide catalysts. *Brazilian Journal of Science*, 3(12), 13-27. <https://doi.org/10.14295/bjs.v3i12.663>
- Shah, M., Hameed, A., Kashif, M., Majeed, N., Muhammad, J., Shah, N., & Hashtoh, H. (2024). Advances in agar-based composites: a comprehensive review. *Carbohydrate Polymers*, 346, 22619. <https://doi.org/10.1016/j.carbpol.2024.122619>
- Shang, C., Shi, L., Zhou, S., Muhmmad, S., Isimjan, T. T., Hu, H., & Yang, X. (2024). Interface engineering of Co₂B–MoO₃/MOF heterojunctions with rich cobalt defects for highly enhanced NaBH₄ hydrolysis. *Inorganic Chemistry Frontiers*, 11(20), 7142-7151. <https://doi.org/10.1039/d4qi01721h>
- Stach, E. A., DeCost, B., Kusne, A. G., Stanev, V., & Maruyama, B. (2021). Autonomous experimentation systems for materials development. *Nature Reviews Materials*, 6, 9-27.
- Sun, H. (2025). Characterization of molecular properties of the potyviral protein HCPro, and their role in the interaction of the virus with its environment. Universidad Autónoma de Madrid, España.
- Sun, H., Ciska, M., Makki, M., Tenllado, F., & Canto, T. (2024). Adaptive substitutions at two amino acids of HCPro modify its functional properties to separately increase the virulence of a potyviral chimera. *Molecular Plant Pathology*, 25(6), e13487. <https://doi.org/10.1111/mpp.13487>
- Sun, H., del Toro, F., Makki, M., Tenllado, F., & Canto, T. (2022). Adaptation of a potyvirus chimera increases its virulence in a compatible host through changes in HCPro. *Plants*, 11(17), 2262. <https://doi.org/10.3390/plants11172262>
- Sun, H., Gul, M., Sakina, Khan, A., Liaqat, Z., Aleena, S., & Ali, A. (2026). Engineering disorder in high-entropy metal oxides for advanced functional applications. *Brazilian Journal of Science*, 5(8), 38-51. <https://doi.org/10.14295/bjs.v5i8.885>
- Sun, H., Ji, D., Ma, C., Pang, R., Yuan, B., Liu, J., Zhang, H., & Zhang, M. (2024). Bioinspired aerogels: ingenious structure, remarkable performance, and versatile applications. *Journal of Materials Chemistry A*, 12(21), 12358-12380. <https://doi.org/10.1039/d4ta00851k>
- Sun, H., Sohail, A., Shah, A., Liaqat, Z., Gul, M., & Liangyu. (2025). From precursors to performance: Diverse synthesis strategies for cerium oxide nanoparticles. *Phytopharmacology Research Journal*, 4(2), 28-42.
- Tahir, N., Zahid, M., Bhatti, I. A., Mansha, A., & Hussain, T. (2021). Metal oxide-based ternary nanocomposites for wastewater treatment. In: *Aquananotechnology*, Chapter 7, Elsevier, 135-158 p. <https://doi.org/10.1016/B978-0-12-821141-0.00022-7>
- Topol, E. (2019). High-performance medicine: The convergence of human and artificial intelligence. *Nature Medicine*, 25, 44-56. <https://doi.org/10.1038/s41591-018-0300-7>
- U. S. Food and Drug Administration. (FDA). (2024). Medical devices. Available in: <https://www.fda.gov/medical-devices>. Accessed on: June 03, 2026.
- Ur Rehman, M., Yin, R., Yang, Z-D., Zhang, G., Liu, Y., Zhang, F-M., Yu, C., & Muhammad, S. (2025). Fabrication and modification of hydrotalcite-based photocatalysts and their composites for CO₂ Reduction: A critical review. *ChemSusChem*, 18(10), e202402333. <https://doi.org/10.1002/cssc.202402333>
- Wang, J., Fazil, P., Shah, M. I. A., Zada, A., Anwar, N., Zain, G. G., Khan, W., Jan, F., & Ateeq, M. (2023). Surface plasmon assisted photocatalytic hydrogen generation with Ag decorated g-C₃N₄ coupled SnO₂ nanophotocatalyst under visible-light driven photocatalysis. *International Journal of Hydrogen Energy*,

- 48(57), 21674-21685. <https://doi.org/10.1016/j.ijhydene.2023.03.048>
- Wang, W., Gao, R., Zhang, L., DONG, Y., Du, Y., Dai, Q., Liu, B., Fang, C., Wang, C., Sun, H., & Huang, W. (2026). Precisely targeting cardiac remodeling nanomachine for restarting healthy heartbeat. *Advanced Healthcare Materials*, 15(3), e03478. <https://doi.org/10.1002/adhm.202503478>
- Yang, J., Hassan, N., Kalsoom, U. E., Mushtaq, F., ul Haq, M. H., & Mahmood, S. (2024). Synthesis of novel Bi/Bi₂O₃@ Al₂O₃ nanocomposites for wastewater treatment, self-cleaning, and corrosion resistance. *New Journal of Chemistry*, 48(37), 16243-16260. <https://doi.org/10.1039/d4nj02556c>
- Yasmeen, H., Zada, A., Li, W., Xu, M., & Liu, S. (2019). Suitable energy platform of Bi₂WO₆ significantly improves visible-light degradation activity of g-C₃N₄ for highly toxic diuron pollutant. *Materials Science in Semiconductor Processing*, 102, 104598. <https://doi.org/10.1016/j.mssp.2019.104598>
- Ye, F., Li, T., Chen, J., Liu, Y., Wu, S., Zada, A., & Dang, A. (2024). Fabrication of high-performance graphene fiber: Structural evolution strategy from a two-step green reduction method. *Ceramics International*, 50(22), 48575-48582. <https://doi.org/10.1016/j.ceramint.2024.09.205>
- Zada, A., & Azizi, S. (2026). Synergistic advanced oxidation and physicochemical treatment strategies for antibiotic removal and resistance mitigation in water. *Asia-Pacific Journal of Chemical Engineering*, e70265. <https://doi.org/10.1002/apj.70265>
- Zahoor, S., Muhammad, S., Kashi, M., Shhzad, N., Liu, Y-C., Celik, C., Ambreen, N., Ali, A., Wu, H-F., Azizi, S., & Wen, S. (2026). Advances in mesoporous nanomaterials for photocatalytic degradation of pollutants: fundamentals, material classifications, challenges and future prospects. *Coordination Chemistry Reviews*, 549, 217239. <https://doi.org/10.1016/j.ccr.2025.217239>
- Zeng, X., & Sun, H. (2025). Enhancing the understanding of complement protein changes in RVO: Insights and suggestions. *Journal of Inflammation Research*, 18, 2781-2782. <https://doi.org/10.2147/JIR.S522685>
- Zhang, B., Zhang, H., Zhu, L., Weng, X., & Sun, H. (2026). Complex research review on environmental risk management of soil microplastic contamination: Treatment technologies and global perspectives. *MSI Journal of Multidisciplinary Research*, 3(4) 1-34. <https://zenodo.org/records/19660481>
- Zhang, B., Zhang, H., Zhu, L., Weng, X., & Sun, H. (2026). Microplastics in the human gastrointestinal system: A comprehensive study of metabolic risks and digestive toxicity. *MSI Journal Multidisciplinary Research*, 3(4), 1-31. <https://zenodo.org/records/19660158>
- Zhao, P., Sun, H., & Han, Q. (2025). Development and application of an intelligent platform for automated recognition of surgical instruments in laparoscopic procedures: a multicenter retrospective study. *International Journal of Surgery*, 111(10), 7379. <https://doi.org/10.1097/JS9.00000000000002726>
- Zhu, H., Sun, H., Dai, J., Hao, J., & Zhou, B. (2024). Chitosan-based hydrogels in cancer therapy: Drug and gene delivery, stimuli-responsive carriers, phototherapy and immunotherapy. *International Journal of Biological Macromolecules*, 282, 137047. <https://doi.org/10.1016/j.ijbiomac.2024.137047>
- Zia, R., Nazir, M. S., Rouf, H., Ahmad, N., Ahmad, F., Ali, Z., & Hassan, S. U. (2025). Modified lignin etched sulphur-doped graphitic carbon nitride for electrochemical sensing of cypermethrin in drinking water: Experimental and theoretical insights. *International Journal of Biological Macromolecules*, 146503. <https://doi.org/10.1016/j.ijbiomac.2025.146503>
- Zou, Z., Mu, Y., Han, M., Hu, H., Zheng, K., Man, Q., Qiu, Z., Wei, L., Zeng, L., & Zhao, T. (2026). Ion storage mechanisms in TiO₂. *Nano Research Energy*, 5(2), e9120207. <https://doi.org/10.26599/NRE.2025.9120207>

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