Mo-Based Nanomaterials for Antibacterial Strategies: A Survey

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Abstract

Molybdenum-based nanomaterials, particularly molybdenum disulfide (MoS), have emerged as promising candidates in the development of innovative antibacterial strategies due to their unique physicochemical properties and potent antimicrobial activity. This survey paper explores the synthesis, properties, and applications of Mo-based nanomaterials, emphasizing green synthesis methods that enhance biocompatibility and sustainability. MoS exhibits a high surface area-to-volume ratio, tunable electronic properties, and the ability to generate reactive oxygen species (ROS), which contribute to its effectiveness against a broad spectrum of pathogens, including antibiotic-resistant strains. The paper discusses various synthesis techniques, such as top-down and bottom-up approaches, highlighting their advantages and challenges in achieving defect-free and scalable production. Furthermore, the survey examines the antibacterial mechanisms of MoS, including ROS generation and membrane disruption, and its applications in healthcare, industry, and environmental remediation. Despite the promising potential, challenges remain in terms of long-term stability, environmental impact, and scalability of production methods. Future research should focus on optimizing synthesis techniques, exploring synergistic effects with existing antimicrobial agents, and assessing the environmental implications of Mo-based nanomaterials. By addressing these challenges, MoS can significantly contribute to sustainable and effective antibacterial solutions, offering a viable approach to combating microbial resistance.

1 Introduction

1.1 Importance of Mo-Based Nanomaterials

Mo-based nanomaterials, especially molybdenum disulfide (MoS_2), play a crucial role in contemporary antibacterial strategies due to their unique physicochemical properties and significant antimicrobial efficacy. Their high surface area-to-volume ratio enhances interactions with microbial cells, facilitating effective antibacterial action [1]. Mo-based nanomaterials disrupt bacterial cell membranes and generate reactive oxygen species (ROS), which are vital in combating bacterial infections. Additionally, their tunable electronic properties allow for precise control over antibacterial performance, making them versatile for healthcare and industrial applications.

Recent advancements in the synthesis of Mo-based nanomaterials have emphasized green methods, which reduce environmental impact while improving biocompatibility. This shift aligns with the increasing demand for sustainable antibacterial solutions across various sectors. Incorporating Mo-based nanomaterials into existing antibacterial frameworks presents a promising strategy to tackle the growing challenge of antibiotic resistance [1].

1.2 Green Synthesis Methods

Green synthesis methods have garnered considerable attention in the fabrication of Mo-based nanomaterials, aligning with sustainable development goals and minimizing environmental impact. These

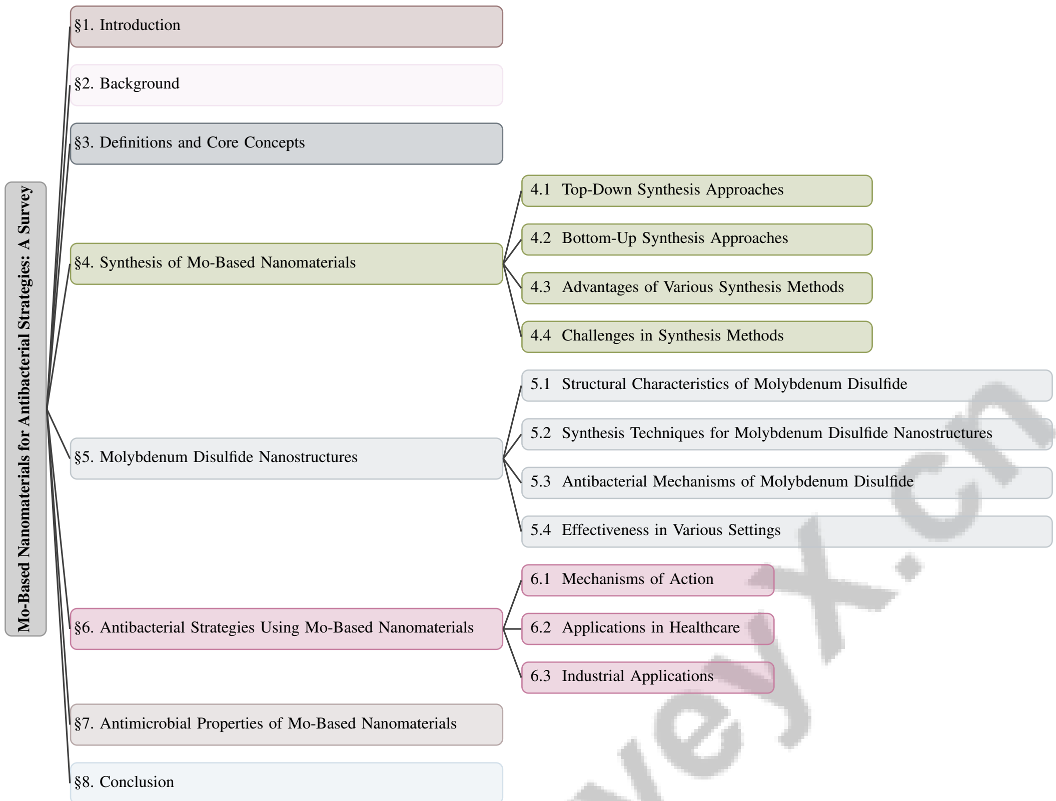

Figure 1: chapter structure

approaches utilize eco-friendly solvents, biological agents, and energy-efficient processes, reducing hazardous by-products. The significance of green synthesis in Mo-based nanomaterials lies in its ability to enhance the biocompatibility and functional properties of nanostructures, making them suitable for diverse antibacterial applications [1].

The production of molybdenum disulfide (MoS_2) nanostructures through green synthesis exemplifies the transition towards sustainable nanotechnology practices. These methods not only lessen ecological footprints but also open avenues for new applications, as the benign synthesis processes often yield nanomaterials with improved biological compatibility. Furthermore, focusing on green synthesis is essential for addressing the environmental implications of nanotechnology, especially as the use of nanomaterials expands across various sectors [1].

Future research should emphasize developing innovative, sustainable synthesis techniques while exploring novel applications of Mo-based nanomaterials. This approach can address both current and emerging challenges, such as antibiotic resistance, while ensuring environmental stewardship [1].

1.3 Structure of the Survey

This survey is systematically organized to provide a comprehensive overview of Mo-based nanomaterials and their applications in antibacterial strategies. The introductory section establishes the significance of Mo-based nanomaterials, particularly molybdenum disulfide, and the relevance of green synthesis methods. The background section elaborates on the chemical properties of Mo-based nanomaterials and their antibacterial roles, offering a detailed understanding of their importance in nanotechnology.

Following this, a section on definitions and core concepts clarifies essential terms and explores the relationship between green synthesis and antibacterial applications. The synthesis of Mo-based nanomaterials is then examined, focusing on top-down and bottom-up approaches, alongside the advantages and challenges associated with these methods.

A dedicated section investigates molybdenum disulfide nanostructures, detailing their structural characteristics, synthesis techniques, and antibacterial mechanisms, as well as their effectiveness in various contexts. The survey further explores the application of Mo-based nanomaterials in developing innovative antibacterial strategies, addressing mechanisms of action and applications in healthcare and industry.

The antimicrobial properties of molybdenum-based nanomaterials are thoroughly analyzed, focusing on their efficacy against diverse pathogens and the factors influencing their antimicrobial activity, such as synthesis methods, structural characteristics, and environmental conditions, as highlighted in recent research by Dr. Nadeem Baig and Dr. Wail Sulaiman Falath at the Center of Research Excellence in Desalination Water Treatment, King Fahd University of Petroleum and Minerals [1]. The survey also discusses challenges related to long-term stability, environmental impact, safety considerations, and scalability of production methods.

The conclusion synthesizes key findings and insights derived from the survey, providing a comprehensive analysis of the current state and future potential of molybdenum-based nanomaterials in antibacterial applications. It highlights specific areas for further investigation, guiding future research efforts in this promising field [1].The following sections are organized as shown in Figure 1.

2 Background

2.1 Chemical Properties of Mo-Based Nanomaterials

Mo-based nanomaterials, particularly molybdenum disulfide (MoS_2), are distinguished by their layered structure, characterized by strong intralayer covalent bonds and weak interlayer van der Waals forces. This configuration facilitates the exfoliation of MoS_2 into monolayers, significantly increasing surface area and reactivity, crucial for antibacterial applications [1]. These materials exhibit exceptional electronic properties, such as a tunable bandgap, allowing precise control over electrical conductivity essential for nanoscale devices and sensors. The transition of MoS_2 from an indirect to a direct bandgap upon monolayer reduction underscores its versatility in electronic and optoelectronic applications [1]. Chemical stability further enhances their utility, as they resist oxidation and degradation, ensuring durability across environments. Their ability to generate reactive oxygen species (ROS) under specific conditions enhances their antimicrobial properties, making them effective in antibacterial roles. Research by Dr. Nadeem Baig and Dr. Wail Sulaiman Falath highlights the development of advanced nanocomposites that improve performance while addressing synthesis challenges of defect-free nanomaterials [1].

2.2 Role of Molybdenum Disulfide in Antibacterial Strategies

Molybdenum disulfide (MoS_2) plays a pivotal role in antibacterial strategies due to its unique physicochemical properties. A key antibacterial mechanism is ROS generation, which induces oxidative stress in bacterial cells, causing cellular damage and death. This is complemented by MoS_2's ability to disrupt bacterial cell membranes, enhancing its antibacterial effectiveness [1]. The high surface area-to-volume ratio of MoS_2 facilitates interactions with bacterial cells, leading to mechanical damage to cell walls and augmented antibacterial properties. Exfoliated monolayers with enhanced electronic properties, like a tunable bandgap, further optimize material-bacterial interactions [1]. The chemical stability and biocompatibility of MoS_2 make it suitable for applications in coatings, films, and composites. Research at the Center of Research Excellence in Desalination Water Treatment emphasizes the potential of modifying synthesis methods and structural configurations to boost MoS_2's antibacterial efficacy. Its versatility in integrating into diverse matrices positions MoS_2 as a promising solution to antibiotic resistance, offering a sustainable alternative to traditional antibiotics [1].

In recent years, the exploration of nanostructures has gained significant attention due to their potential applications in various fields, particularly in antimicrobial strategies. To better understand the interconnections among the core concepts associated with these nanostructures, it is essential to consider their hierarchical structure. Figure 2 illustrates this structure, highlighting the key properties, applications, and the pivotal role of green synthesis methods in enhancing MoS2 nanostructures for sustainable antibacterial solutions. This visual representation not only underscores the relevance of

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these concepts but also provides a comprehensive overview that enhances our understanding of the subject matter.

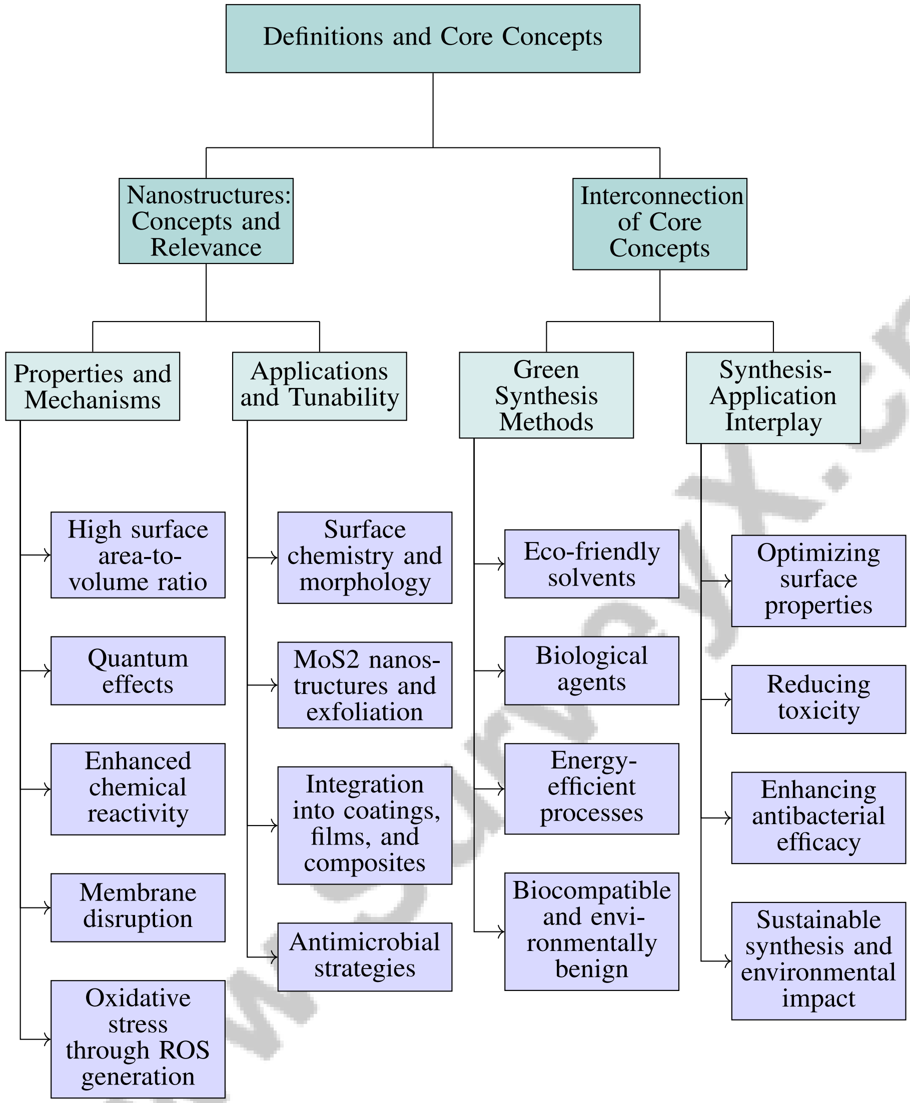

Figure 2: This figure illustrates the hierarchical structure of core concepts related to nanostructures and their relevance in antimicrobial strategies, highlighting key properties, applications, and the role of green synthesis methods in enhancing MoS2 nanostructures for sustainable antibacterial solutions.

3 Definitions and Core Concepts

3.1 Nanostructures: Concepts and Relevance

Nanostructures, defined by their nanoscale dimensions, are pivotal in antimicrobial strategies due to their unique physicochemical properties that differ from bulk materials. These properties include a high surface area-to-volume ratio, quantum effects, and enhanced chemical reactivity, which facilitate interactions with microbial cells, leading to mechanisms like membrane disruption and oxidative stress through reactive oxygen species (ROS) generation [1]. These interactions are crucial for the antimicrobial efficacy of nanostructures, enhancing their ability to penetrate and act against bacterial cells.

The tunability of nanostructures, particularly regarding surface chemistry and morphology, enhances their applicability in antimicrobial contexts. Molybdenum disulfide (MoS_2) nanostructures, for

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instance, can be exfoliated into monolayers, increasing surface area and interaction with bacterial membranes, aiding in mechanical disruption [1]. Furthermore, MoS_2's electronic properties can be tailored to optimize bacterial interactions, boosting antimicrobial performance.

Nanostructures' adaptability allows their integration into various matrices such as coatings, films, and composites, broadening their application in antibacterial strategies. This versatility is vital for developing sustainable antimicrobial solutions that effectively combat pathogens while minimizing environmental impact. The ability to engineer nanostructures with specific properties to target microbial threats underscores their potential in addressing antibiotic resistance and fostering innovative antimicrobial approaches [1].

3.2 Interconnection of Core Concepts

The integration of green synthesis methods and antibacterial strategies is essential for advancing molybdenum-based nanomaterials, particularly MoS_2 nanostructures, as sustainable solutions against microbial resistance. Green synthesis employs eco-friendly solvents, biological agents, and energy-efficient processes, contributing to the creation of biocompatible and environmentally benign nanomaterials. This approach not only reduces the ecological footprint of nanomaterial production but also enhances their functional properties for antibacterial applications [1].

Implementing green synthesis in MoS_2 nanostructure fabrication optimizes surface properties and reduces toxicity, crucial for effective antimicrobial action. The improved surface area-to-volume ratio and ROS generation capacity are further enhanced through these methods, increasing MoS_2's interaction with bacterial cells and elevating its antibacterial efficacy [1]. This synthesis-application interplay is vital for developing innovative antibacterial strategies addressing the growing challenge of antibiotic resistance.

Emphasizing sustainable synthesis aligns with broader goals of minimizing environmental impact and promoting safe nanotechnology use in healthcare and industry. By leveraging green synthesis, researchers can design Mo-based nanomaterials effective against diverse pathogens while ensuring safety in applications like coatings, films, and composites. This comprehensive approach ensures that developed antibacterial strategies are both effective and sustainable, paving the way for long-term solutions in combating microbial resistance [1].

4 Synthesis of Mo-Based Nanomaterials

Molybdenum-based compounds, particularly molybdenum disulfide (MoS_2), are prominent in nanomaterials research due to their distinct properties and potential applications. The synthesis of these nanomaterials employs top-down and bottom-up techniques, each offering specific benefits and challenges influencing the characteristics and applications of the materials. Table 1 provides a comparative overview of the features associated with top-down and bottom-up synthesis approaches for Mo-based nanomaterials, emphasizing their respective control precision, production scale, and morphology variety. This section delves into top-down synthesis methods, which reduce bulk materials to nanoscale dimensions, setting the stage for an in-depth analysis of their mechanisms, advantages, and challenges as highlighted by research at the Center of Research Excellence in Desalination Water Treatment at King Fahd University of Petroleum and Minerals [1].

4.1 Top-Down Synthesis Approaches

Top-down synthesis methods deconstruct bulk materials into nanoscale structures through mechanical, chemical, or thermal processes. These methods are vital for fabricating MoS_2 nanostructures, enabling precise control over size and morphology, crucial for enhancing antimicrobial properties [1]. As illustrated in Figure 3, which highlights the various top-down synthesis approaches for MoS_2 nanostructures, mechanical exfoliation, a prevalent technique, employs mechanical forces to separate MoS_2 layers into thinner sheets or monolayers. This method leverages weak van der Waals forces to produce high-quality nanosheets with minimal defects, which exhibit enhanced electronic and mechanical properties for applications like antibacterial coatings [1].

Chemical exfoliation uses chemical agents to intercalate and exfoliate bulk MoS_2, facilitating scalable production of nanosheets with controlled thickness and introducing functional groups to improve

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reactivity and interaction with microbial cells, thus enhancing antimicrobial efficacy [1]. Additionally, liquid-phase exfoliation disperses bulk material in a solvent and applies ultrasonic energy to separate layers, providing simplicity and the capability to produce large quantities of uniformly sized nanosheets. Optimizing parameters such as solvent choice and ultrasonic power tailors the properties of MoS_2 nanostructures for specific antibacterial applications [1].

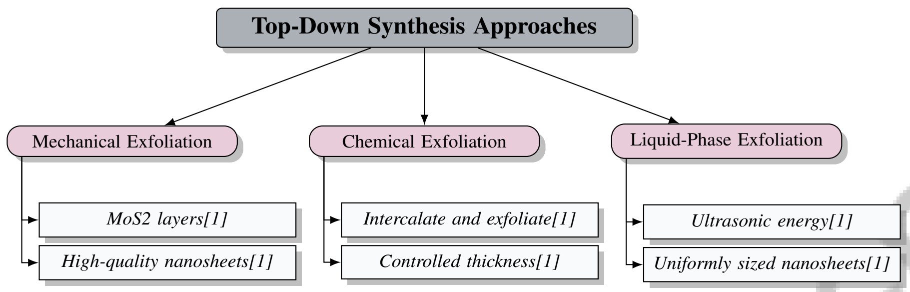

Figure 3: This figure illustrates the top-down synthesis approaches for MoS2 nanostructures, highlighting mechanical, chemical, and liquid-phase exfoliation techniques [1].

4.2 Bottom-Up Synthesis Approaches

Bottom-up synthesis methods construct nanoscale structures from atoms or molecules through chemical reactions and self-assembly. Research by Dr. Nadeem Baig and Dr. Wail Sulaiman Falath at the Center of Research Excellence in Desalination Water Treatment emphasizes these techniques for fabricating MoS_2 nanostructures, allowing precise control over composition, morphology, and size, which are essential for optimizing antimicrobial properties and enhancing effectiveness in various applications, including advanced nanocomposite membranes for desalination [1]. Chemical vapor deposition (CVD), a prominent bottom-up method, deposits gaseous precursors onto a substrate, forming thin MoS_2 films. CVD is crucial for developing high-quality monolayer MoS_2 with uniform thickness and excellent crystallinity, essential for high-performance electronic and antibacterial applications. The tunability of CVD parameters such as temperature, pressure, and precursor concentration enhances its versatility in fabricating MoS_2 with tailored properties [1]. Hydrothermal synthesis uses high-temperature and high-pressure aqueous solutions to form MoS_2 nanostructures, offering simplicity and scalability. This method can produce various morphologies, including nanosheets, nanoflowers, and nanorods, with customizable properties for enhanced antimicrobial efficacy [1]. Solvothermal synthesis, a variant of hydrothermal synthesis, employs organic solvents to dissolve precursor materials, enabling controlled growth of MoS_2 nanostructures with desirable properties, effectively producing MoS_2 with unique morphologies and surface properties to improve interaction with bacterial cells and enhance antimicrobial efficacy [1].

4.3 Advantages of Various Synthesis Methods

The synthesis of Mo-based nanomaterials, particularly MoS_2, offers various methods, each with distinct advantages tailored to specific applications. Top-down approaches like mechanical and chemical exfoliation yield high-quality nanosheets with controlled thickness and minimal defects, preserving the intrinsic properties of the bulk material while enhancing surface area and reactivity [1]. Conversely, bottom-up methods such as CVD and hydrothermal synthesis provide precise control over the composition and morphology of nanostructures. CVD enables the production of monolayer MoS_2 with excellent crystallinity, crucial for high-performance electronic and optoelectronic applications. The adaptability of CVD parameters further enhances its capability to fabricate MoS_2 with specific properties [1]. Hydrothermal and solvothermal synthesis methods offer simplicity, scalability, and the ability to produce diverse morphologies, facilitating the formation of nanostructures with unique surface properties that enhance their interaction with bacterial cells. The flexibility of these methods allows for customization of MoS_2 nanostructures to meet various antibacterial application requirements [1].

4.4 Challenges in Synthesis Methods

The synthesis of Mo-based nanomaterials, particularly MoS_2, presents challenges affecting structural integrity and functional properties. A primary challenge is producing defect-free nanomaterials, as defects can significantly alter the electronic, mechanical, and chemical characteristics of the nanostructures. Such defects may arise during synthesis processes like mechanical exfoliation or CVD, compromising the advantageous properties sought in antibacterial applications and beyond [1]. Achieving uniformity and consistency in the size and morphology of synthesized nanostructures is another challenge, as variations can lead to performance inconsistencies, especially in applications requiring precise control over surface properties and reactivity. This issue is often exacerbated in scalable synthesis methods, where maintaining consistent reaction conditions across large batches proves difficult [1]. Optimizing synthesis parameters such as temperature, pressure, and precursor concentration is crucial yet challenging, as deviations can result in unwanted phases or amorphous structures lacking the beneficial properties of crystalline MoS_2. A thorough understanding of the underlying mechanisms is essential for achieving reproducibility and high-quality nanomaterials [1]. Environmental and economic considerations also pose challenges in synthesizing Mo-based nanomaterials. The use of hazardous chemicals and high-energy processes raises concerns about the environmental impact and sustainability of these techniques. Developing green synthesis approaches that minimize ecological footprints while maintaining nanomaterial quality and performance is imperative [1].

Feature	Top-Down Synthesis Approaches	Bottom-Up Synthesis Approaches
Control Precision	Size And Morphology	Composition And Morphology
Production Scale	High-quality Nanosheets	Scalable Nanostructures
Morphology Variety	Limited TO Nanosheets	Diverse Morphologies

Table 1: This table presents a comparative analysis of top-down and bottom-up synthesis approaches for molybdenum disulfide (MoS) nanostructures. It highlights key features such as control precision, production scale, and morphology variety, illustrating the distinct advantages and limitations of each method in the context of nanomaterial synthesis.

5 Molybdenum Disulfide Nanostructures

5.1 Structural Characteristics of Molybdenum Disulfide

Molybdenum disulfide (MoS_2) is characterized by a unique layered structure with a molybdenum atom plane flanked by sulfur atom planes. The weak van der Waals forces between these layers enable exfoliation into monolayers, which is essential for enhancing antibacterial properties [1]. Exfoliation increases the surface area-to-volume ratio, improving interaction with bacterial cells and thus boosting antimicrobial activity. The structural transition from an indirect to a direct bandgap in monolayer MoS_2 enhances its electronic properties, facilitating reactive oxygen species (ROS) generation under light exposure, which induces oxidative stress and bacterial cell death [1]. The mechanical flexibility and stability of MoS_2 allow its integration into various composite materials, such as nanocomposite membranes for desalination, providing durable antibacterial surfaces that withstand physical and chemical stresses [1]. Moreover, the surface chemistry of MoS_2 can be modified to enhance microbial membrane interactions, promoting bacterial cell wall disruption and increasing antibacterial efficacy [1].

5.2 Synthesis Techniques for Molybdenum Disulfide Nanostructures

The synthesis of MoS_2 nanostructures involves top-down and bottom-up approaches, each offering specific benefits for antibacterial applications. Top-down methods, such as mechanical exfoliation, produce high-quality nanosheets by applying mechanical forces to bulk MoS_2, exploiting weak van der Waals forces to isolate monolayers with minimal defects [1]. Chemical exfoliation uses chemical agents for scalable production and surface functionalization, optimizing thickness and lateral dimensions for enhanced antibacterial efficacy [1]. Bottom-up techniques, like chemical vapor deposition (CVD), deposit gaseous precursors onto substrates, forming monolayer MoS_2 with excellent crystallinity and uniformity, with tunable properties [1]. Hydrothermal synthesis, using high-temperature and pressure aqueous solutions, produces diverse morphologies that enhance antimicrobial activity [1]. Solvothermal synthesis with organic solvents creates MoS_2 with unique morphologies and surface properties, optimizing bacterial interactions [1].

5.3 Antibacterial Mechanisms of Molybdenum Disulfide

MoS_2 employs several antibacterial mechanisms, including ROS generation, which induces oxidative stress and disrupts cellular components, leading to bacterial cell death [1]. Increased surface area in monolayer structures enhances bacterial interaction. MoS_2 also disrupts bacterial cell membranes through physical interactions, causing mechanical damage and compromising membrane integrity [1]. Additionally, MoS_2 penetrates biofilms, enhancing efficacy against biofilm-associated infections. Its electronic properties, particularly the tunable bandgap, aid in boosting antibacterial activity through photoexcitation, generating electron-hole pairs that participate in redox reactions, promoting ROS production and antibacterial action [1]. These multifaceted antibacterial mechanisms are enhanced by MoS_2's electronic properties, tailored for diverse antimicrobial applications, as highlighted by research from Dr. Nadeem Baig and Dr. Wail Sulaiman Falath [1].

5.4 Effectiveness in Various Settings

MoS_2 is highly effective across various applications due to its physicochemical properties and synthesis versatility. In healthcare, MoS_2 is used in antibacterial coatings for medical devices, where ROS generation and membrane disruption prevent infections [1]. It enhances wound dressings and surgical sutures, reducing infection risks and promoting healing. In industrial settings, MoS_2 acts as an antimicrobial agent in water treatment systems, efficiently removing bacterial contaminants and maintaining cleanliness by penetrating and disrupting biofilms [1]. Its effectiveness extends to environmental applications, such as self-cleaning surfaces and air purification systems, where photo-induced ROS generation degrades pollutants and eliminates pathogens, improving air quality [1]. Additionally, MoS_2 is integrated into food packaging as an antimicrobial barrier, prolonging shelf life due to its non-toxic nature and robust antibacterial activity, making it ideal for applications prioritizing safety and hygiene [1].

6 Antibacterial Strategies Using Mo-Based Nanomaterials

6.1 Mechanisms of Action

Molybdenum-based nanomaterials, notably molybdenum disulfide (MoS_2), exhibit antibacterial efficacy through several mechanisms leveraging their unique physicochemical properties. A key mechanism is the generation of reactive oxygen species (ROS), which induces oxidative stress, damaging bacterial lipids, proteins, and nucleic acids, leading to cell death [1]. This ROS generation is enhanced in monolayer or few-layer MoS_2, where increased surface area facilitates bacterial interactions and more effective ROS production.

Mo-based nanomaterials also physically disrupt bacterial membranes. The high surface area-to-volume ratio of MoS_2 nanosheets promotes close interaction with bacterial membranes, causing mechanical damage and compromising membrane integrity, leading to cellular content leakage and loss of membrane potential [1]. The layered structure of MoS_2 enables biofilm penetration, increasing efficacy against biofilm-associated infections.

The electronic properties of MoS_2, including its tunable bandgap, further enhance antibacterial activity. Light exposure induces photoexcitation in MoS_2, generating electron-hole pairs that participate in redox reactions, promoting ROS production and antibacterial action. This photo-induced mechanism provides an additional pathway for enhancing MoS_2's antibacterial performance, particularly in light-assisted applications [1].

The multifaceted antibacterial mechanisms of molybdenum-based nanomaterials, encompassing ROS generation, membrane disruption, and biofilm penetration, highlight MoS_2's versatility as an antibacterial agent, as demonstrated by recent research from Dr. Nadeem Baig and Dr. Wail Sulaiman Falath [1].

6.2 Applications in Healthcare

Mo-based nanomaterials, especially MoS_2, are increasingly used in healthcare due to their potent antibacterial properties and versatility. A significant application is in antibacterial coatings for medical devices and implants, where MoS_2 utilizes its ROS-generating ability to prevent bacterial colonization and biofilm formation, reducing device-associated infection risks [1].

MoS_2 is also explored for wound dressings and surgical sutures, where its antibacterial efficacy accelerates healing and reduces post-surgical infection rates. Its integration into these materials enhances antimicrobial activity, providing a protective barrier against pathogens. The biocompatibility and non-toxic nature of MoS_2 ensure safe application in contact with biological tissues, allowing effective antibacterial action without compromising patient safety [1].

In drug delivery systems, MoS_2 nanoparticles improve targeted delivery and controlled release of therapeutic agents. The high surface area and tunable electronic properties facilitate drug adsorption and conjugation, enhancing stability and bioavailability, which is beneficial for treating bacterial infections by enabling precise antibiotic delivery to improve therapeutic outcomes and minimize side effects [1].

Additionally, MoS_2 is used in developing biosensors for rapid detection of bacterial pathogens. Its electronic properties, including tunable bandgap and high conductivity, allow the creation of sensitive sensors capable of detecting bacterial antigens or DNA sequences, improving diagnostic accuracy and speed in clinical settings [1].

The diverse applications of Mo-based nanomaterials in healthcare—spanning infection prevention, wound healing, drug delivery, and diagnostics—demonstrate their potential to enhance healthcare technologies. MoS_2's properties, such as electrical conductivity, mechanical strength, and biocompatibility, position it as a promising nanomaterial for innovative antimicrobial applications and advanced drug delivery systems [1].

6.3 Industrial Applications

Mo-based nanomaterials, particularly MoS_2, hold significant potential in various industrial applications due to their unique physicochemical properties. A primary application is lubrication, where MoS_2's layered structure and low friction coefficient make it an ideal solid lubricant in mechanical systems. The weak van der Waals forces between MoS_2 layers facilitate easy sliding, reducing wear and friction, enhancing machinery efficiency and lifespan [1].

In electronics, MoS_2 is explored for fabricating thin-film transistors and other devices. Its tunable electronic properties, including bandgap and high carrier mobility, enable the development of high-performance components suitable for flexible and wearable technologies, advancing next-generation electronic devices requiring lightweight and efficient materials [1].

Mo-based nanomaterials are also recognized in catalysis, where their high surface area and chemical stability render them effective catalysts for various reactions. MoS_2 demonstrates excellent catalytic activity in hydrogen evolution reactions, positioning it as a candidate for energy conversion and storage applications, such as fuel cells and batteries. Tailoring MoS_2's surface properties through doping and functionalization enhances its catalytic performance, expanding its industrial application scope [1].

In environmental remediation, MoS_2 is used for adsorbing and degrading pollutants, valuable for water and air purification systems. Its high adsorption capacity and photocatalytic activity facilitate efficient removal of organic and inorganic contaminants, contributing to improved environmental quality and sustainability. This application addresses pollution and resource management challenges in industrial settings [1].

The extensive industrial applications of molybdenum-based nanomaterials span critical sectors such as lubrication, electronics, catalysis, and environmental remediation. Research by Dr. Nadeem Baig and Dr. Wail Sulaiman Falath emphasizes ongoing advancements in synthesizing and applying these nanomaterials, highlighting their transformative potential across diverse fields [1]. MoS_2's unique properties make it an attractive material for advancing industrial technologies while addressing challenges related to efficiency, sustainability, and environmental impact.

7 Antimicrobial Properties of Mo-Based Nanomaterials

Molybdenum-based nanomaterials, particularly molybdenum disulfide (MoS_2), exhibit broad-spectrum antimicrobial properties effective against bacteria, fungi, and viruses. These properties, rooted in unique physicochemical characteristics such as high surface area and reactive oxygen species (ROS) generation, position MoS_2 as a promising candidate for diverse antimicrobial applications [1].

7.1 Effectiveness Against Various Pathogens

MoS_2 demonstrates significant antimicrobial efficacy against Gram-positive and Gram-negative bacteria, fungi, and viruses. Its ability to generate ROS induces oxidative stress, disrupting cellular components and proving especially effective against antibiotic-resistant strains. MoS_2 also penetrates and disrupts biofilms, which are typically resistant to conventional treatments, and exhibits antifungal properties by disrupting fungal cell membranes. Additionally, MoS_2 shows potential antiviral activity by inactivating viral particles through ROS generation and interactions with viral envelopes [1].

7.2 Mechanisms of Antimicrobial Action

The antimicrobial efficacy of MoS_2 is attributed to several mechanisms. ROS generation plays a primary role, inducing oxidative stress that disrupts vital cellular components. The high surface area-to-volume ratio facilitates interaction with microbial cells, leading to membrane disruption and biofilm penetration. Additionally, MoS_2's electronic properties, such as tunable bandgap, enhance antimicrobial activity through photoexcitation, generating electron-hole pairs that drive ROS production [1].

7.3 Factors Influencing Antimicrobial Activity

The antimicrobial activity of MoS_2 is influenced by structural characteristics like size and surface area. Smaller nanosheets with higher surface area-to-volume ratios exhibit greater activity. Synthesis methods impact properties such as crystallinity and defect density, affecting ROS generation and membrane disruption capabilities. Surface functionalization and environmental conditions, including pH and light exposure, further modulate activity [1].

7.4 Challenges in Long-Term Stability

Long-term stability challenges for MoS_2 include susceptibility to oxidation and aggregation, which reduce antimicrobial efficacy. Mechanical stability in composites is crucial to prevent delamination and maintain antibacterial properties. Potential environmental leaching raises concerns about ecological and human health impacts, necessitating strategies for enhanced stability and safety [1].

7.5 Environmental Impact and Safety Considerations

Environmental impact and safety considerations are critical for MoS_2 applications. Potential release into ecosystems poses risks due to bioaccumulation and toxicity. Comprehensive toxicity assessments and green synthesis methods are essential to minimize adverse effects and align with sustainable development goals. Understanding MoS_2 transformation in the environment is vital for predicting long-term impacts [1].

7.6 Scalability of Production Methods

Benchmark	Size	Domain	Task Format	Metric

Table 2: This table provides an overview of the representative benchmarks used to evaluate the scalability of MoS extsubscript production methods. It includes details on the size, domain, task format, and metric associated with each benchmark. Such comprehensive information is crucial for assessing the effectiveness and potential of various production techniques.

Scalability of MoS_2 production is vital for widespread application. Table 2 presents a detailed examination of the representative benchmarks pertinent to the scalability of MoS_2 production methods,

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highlighting key aspects such as size, domain, task format, and metric. Top-down methods like exfoliation face challenges in quality and yield, while bottom-up approaches such as chemical vapor deposition and hydrothermal synthesis offer potential for scalable, high-quality production. Addressing uniformity and defect-free production is crucial for commercial integration and maintaining MoS_2's unique properties [1].

8 Conclusion

The survey highlights the transformative potential of Mo-based nanomaterials, particularly molybdenum disulfide (MoS_2), in developing advanced antibacterial strategies. The distinctive physicochemical properties of MoS_2, such as its extensive surface area, adjustable electronic features, and ability to produce reactive oxygen species, render it highly effective against various pathogens, including those resistant to antibiotics. Green synthesis methods have emerged as a pivotal approach, enhancing both the biocompatibility and environmental sustainability of these nanomaterials while addressing the ecological issues associated with traditional synthesis methods.

Despite these advancements, challenges persist in the synthesis of Mo-based nanomaterials, including the production of defect-free materials, consistency in size and morphology, and the scalability of synthesis processes. Overcoming these hurdles is crucial for optimizing the functional attributes of MoS_2 and broadening its application in diverse antibacterial settings. Future research should focus on refining synthesis methods to enhance both the quality and scalability of MoS_2, as well as exploring new applications in healthcare, industry, and environmental management.

The outlook for Mo-based nanomaterials in antibacterial applications is promising, with future research directions including the study of their synergistic interactions with existing antimicrobial agents, the development of multifunctional nanocomposites, and the assessment of their long-term stability and environmental impact. By advancing our understanding of these materials and addressing current challenges, MoS_2 can play a significant role in combating microbial resistance globally and fostering sustainable antibacterial solutions.

References

[1] Nadeem Baig, Irshad Kammakakam, and Wail Falath. Nanomaterials: A review of synthesis methods, properties, recent progress, and challenges. *Materials advances*, 2(6):1821–1871, 2021.