SYNTHESIS AND CHARACTERIZATION OF INORGANIC COMPOUNDS FOR ANTIMICROBIAL APPLICATIONS

Dr. Anil Kumar

Department of Chemistry ,D.A.V(PG)College Dehradun
anilpaldav@gmail.com

ABSTRACT

Antimicrobial resistance has been growing in recent years, making it a pressing need for the development of new antimicrobial materials that are effective against a wide range of microorganisms with new action points. Inorganic compounds, especially metal and metal oxide-based materials, have proved to be potential antimicrobial agents because of their unique physicochemical characteristics, stability and multiple antimicrobial action mechanisms. The aim of the research is the synthesis and characterization of antimicrobial inorganic compounds with regard to their structure, morphology, chemical, optical and biological properties. The synthesized materials were characterized through advanced characterization tools such as X-ray diffraction (XRD), scanning electron microscopy (SEM), transmission electron microscopy (TEM), Fourier transform infrared (FTIR) and UV–Visible spectroscopy. Structural analysis confirmed the presence of the crystalline inorganic phases, while the micro structural investigations showed a nanoscale morphology and a particle size distribution. The functional properties that give antimicrobial activity were proven by optical and chemical analysis. Representative bacterial strains were used to assess its antimicrobial effect, which was found to be effective through generation of ROS, release of metal ions and membrane disruption. The results clearly show the great possibilities of inorganic compounds for biomedical coatings, materials for wound treatment, systems for cleaning the environment, and surface antimicrobial applications. Future efforts should be directed towards sustainable methods of synthesis, toxicity assessment, and scaling up production of advanced inorganic antimicrobial materials.

Keywords

The inorganic compounds, antimicrobial activity, metal oxide nanoparticles, nanomaterial characterization, and antimicrobial resistance are the contents for the study.

1. INTRODUCTION

1.1 Global Challenge of Antimicrobial Resistance

Antimicrobial resistance (AMR) is now one of the biggest challenges in the global health care system. Unnecessary and repeated use of antimicrobial agents has led to emergence of resistant

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microorganisms, limiting the effectiveness of available antimicrobial agents. Resistance to antibiotics can occur in several different ways, such as antibiotic resistance in bacteria, which can modify their targets, degrade antibiotics or decrease the permeability of the cell (Levy and Marshall, 2004). As a result, infections with multidrug resistant microorganisms have made the treatment of the disease more complicated, costlier, and lethal.

With the scarcity of novel antibiotics, there is an urgent need to look for alternative antimicrobial interventions. Most of the traditional antibiotics target specific pathways of bacteria, but the bacteria can quickly become resistant to these pathways. Thus, material with wide spectrum antimicrobial activity by diverse mechanisms has been a subject of great scientific interest. Inorganic compounds, especially those composed of metals and metal oxides, have been identified as promising antimicrobial alternatives due to their ability to exert physical and chemical action against microorganisms that is hard for bacteria to resist (Huh and Kwon, 2011).

The nanocomponents also utilize inorganic antimicrobial materials to produce unique physicochemical properties at the nanoscale, thus enhancing the potential applications for this material. The surface-area-to-volume ratio, surface reactivity, and increased interaction with microbial cells are three other properties of nanomaterials compared with bulk materials (Hajipour et al., 2012). Such properties enable inorganic nanoparticles to exhibit good antimicrobial effect at comparatively low concentration levels.

1.2 Inorganic compounds used for antimicrobial applications and their role

Particularly, inorganic compounds have received a lot of attention as antimicrobial agents because of their chemical stability, durability and wide activity spectrum. The functional properties of inorganic materials remain unaffected in various environmental conditions, which will enable them to be used in a number of applications such as surface coatings, food packaging, environmental protection and healthcare.

Silver (Ag), Copper (Cu), Zinc (Zn) and oxide form of them like zinc oxide (ZnO), titanium dioxide (TiO_2) and copper oxide (CuO) have been found to possess remarkable antimicrobial properties. Inorganic materials with silver have been extensively studied because silver ions can bind with proteins, enzymes and nucleic acids in bacteria, disrupting essential cellular processes (Rai et al., 2009). Likewise copper-containing materials have antimicrobial benefits due to copper ion release and oxidative stress generation and can be useful for antimicrobial surfaces and protective coatings.

Metal oxide nanoparticles offer further benefits as they can also be used in a photocatalytic antimicrobial reaction due to their semiconductor properties. Under appropriate conditions, for instance, titanium dioxide and zinc oxide can produce ROS, causing oxidative damage to microbial cells (Foster et al., 2011). Their properties have led to their use in biomedical devices, wound healing, water purification systems and antimicrobial coatings.

Structural properties such as the particle size, shape, crystallinity, surface area and chemical composition play a significant role in the effectiveness of inorganic antimicrobial compounds.

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Hence, it is crucial to accomplish the synthetic control and thorough characterization of these materials to ensure their enhanced antimicrobial activity and lower toxicity.

1.3 The mechanisms of action of antimicrobial activity of Inorganic Compounds

Mechanisms of antimicrobial activity of inorganic compounds are interrelated. One of the major mechanisms is the production of reactive oxygen species (ROS) such as hydroxyl radicals, superoxide radicals and hydrogen peroxide. These very reactive molecules can rupture the membranes, proteins and genetic material of bacteria, resulting in the death of the microbes (Kreibig and Vollmer, 1995).

Release of metal ions is another significant mechanism. Biologically active inorganic materials like silver, copper and zinc compounds can react with the cell components of bacteria. These ions can bind to proteins that have sulfur groups, affect enzyme function and disrupt metabolic pathways required for the survival of microorganisms (Morones et al., 2005).

Also, inorganic nanoparticles can have direct interaction with the bacterial cell membranes. By virtue of their small size they come into close contact with microbial surfaces, which leads to a deformation of the membrane, an increased permeability and leakage of intracellular components. Irritation of the membrane, oxidative stress and intracellular damage all play a part in the potent antimicrobial properties of inorganic materials.

1.4 Research Aim and Objectives

This research is designed to synthesize and characterize inorganic compounds for antimicrobial purpose to study structural, morphological, chemical and biological properties for their evaluation.

This study aims at:

- To prepare inorganic compounds by appropriate methods.
- To study the structural and morphological features of the prepared materials.
- Analyse the chemical and optical properties by advanced characterization techniques.
- To assess antimicrobial activity against the selected microbial strains.
- To correlate the material properties to antimicrobial activity.

2. LITERATURE REVIEW

2.1 The general overview of the antimicrobial inorganic materials

Rai et al. (2009) investigated the antimicrobial potential of silver nanoparticles and highlighted the importance of inorganic materials as alternatives to conventional antimicrobial agents. Their research revealed the unique physicochemical properties of the metal-based nanoparticles such as high surface area, enhanced reactivity, and controlled release of ions that are responsible for their strong antimicrobial activity. In contrast to the usual biological pathway that the antibiotic attacks, inorganic nanoparticles can attack several components of the cell at once, making it less likely that the targets will become resistant quickly. There has

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been a significant amount of literature on silver, copper, zinc oxide, and titanium dioxide because they can inhibit a wide variety of microorganisms.

Hajipour et al. (2012) summarized the progress made in the field of antimicrobial nanomaterials and found that the nanoscale inorganic materials exhibit enhanced biological activity over their bulk counterparts. The authors described that, with decreasing size of material to the nanoscale, the surface-to-volume ratio would be greater, which would mean that there would be a larger surface area for interaction between the nanoparticles and the microbial cells. This increased contact results in the disruption of the membrane, generation of oxidative stress and the damage of the intracellular environment. The study also highlighted that the antimicrobial activity of the inorganic compounds is greatly influenced by particle morphology, surface chemistry and synthesis conditions.

Huh and Kwon (2011) proposed a new term “nanoantibiotics” and suggested inorganic nanomaterials as potential alternatives for the fight against antibiotic-resistant microorganisms. They showed that nanoparticles can address several drawbacks of conventional antibiotics as they have antimicrobial activities through physical disruption, releasing of metal ions and generation of reactive oxygen species. Such properties have caused the interest in development of inorganic compounds for medical coatings, wound treatment, food preservation and for environmental applications.

2.2 Metal-Based Antimicrobial Nanomaterials

2.2.1 Silver-Based Compounds

Bactericidal effect of silver nanoparticles was investigated by Morones et al. (2005) and they reported their efficacy against both Gram-positive and Gram-negative bacteria. The authors found that the silver nanoparticles have a direct interaction with the membrane of the bacteria, which leads to changes in the structure leading to leakage of the internal components of the bacteria. In addition, silver ions released interact with proteins containing sulphur, and genetic materials, which helps to inhibit certain cellular processes.

Rai et al., (2009) went on to say that silver-based antimicrobial compounds are one of the most successful inorganic antimicrobial systems due to its broad-spectrum activity and long-lasting effect. Silver ions can disrupt the enzymes of bacteria, its respiratory processes, and replication of DNA, resulting in potent antimicrobial activity. Because of these characteristics, silver containing materials have found their way into water purification, medical devices, wound dressings, and coatings.

Pal et al (2007) showed that the antimicrobial activity of silver nanoparticles is affected by the size and shape of the nanoparticles. Smaller nanoparticles have higher antibacterial activity due to higher surface area and the interaction of the nanoparticles with the microbial cells. The significant finding will focus on the need to control the synthesis parameters for optimum antimicrobial performance.

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2.2.2 Copper-Based Antimicrobial Compounds

Grass et al. (2011) investigated antimicrobial materials based on copper and found that copper has a high antimicrobial activity because it can release copper ions and cause oxidative stress. Copper ions may interact with bacterial proteins, disrupt metabolic pathways and be responsible for cell destruction. The properties render copper-based compounds as an effective antimicrobial surface and a protective coating.

Ren et al. (2009) studied copper oxide nanoparticles and concluded that the copper nanoscale material exhibits better antimicrobial properties than traditional copper materials. The higher activity was explained by the higher surface interaction and the constant ion release. Copper oxide nanoparticles have thus been suggested as valuable candidates in the fields of applications that need long lasting antimicrobial activity.

2.2.3 Zinc Oxide-Based Materials

Raghupathi et al. (2011) have examined zinc oxide nanoparticles and have concluded that the nanoparticles have high antibacterial activity against various bacterial species. They found that the smaller the size of the ZnO nanoparticles, the more potent the antimicrobial activity, as a result of increased surface defects and increased production of reactive oxygen species. The study showed that the ZnO nanoparticles are capable of disrupting bacterial membrane and reducing the growth of bacteria.

Jones et al. (2008) investigated the antimicrobial properties of zinc oxide and noted its benefits of chemical stability, low cost, and low toxicity in comparison to other metal-containing nanoparticles. The photocatalytic and antimicrobial properties of ZnO nanoparticles have spurred their application in food packaging, medical coatings, and environmental protection.

2.3 The antimicrobial applications of Metal Oxide Nanocomposites are discussed in this section

Foster et al. (2011) studied the antimicrobial properties of the system based on titanium dioxide and made it clear that the photo-catalytic metal oxides produce Reactive Oxygen Species when they are irradiated by light. These are active species that attack microbial membranes, proteins and DNA, leading to effective microbial inactivation. TiO_2-based material has thus been studied for use in self-cleaning surfaces, antimicrobial coatings, and technologies for water treatment.

Stoimenov et al. (2002) investigated the antimicrobial properties of metal oxide nanoparticles, focusing on interactions with the surface and chemical reactions with the microbial cells, and found that compounds like CaO, MgO and ZnO have antimicrobial properties. They concluded that metal oxide nanoparticles can be used as a flexible platform for the design of antimicrobial materials with controlled properties.

Azam et al. (2012) compared various metal oxide nanoparticles and showed that the size of the particles, their surface area and chemical composition affect the antimicrobial activity. They found that incorporating inorganic compounds into nanocomposites was an effective way of

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enhancing the antimicrobial properties due to the synergistic effect of various antimicrobial mechanisms, including ROS production and ion release.

2.4 The synthesis strategies of inorganic antimicrobial compounds are addressed

Cushing et al. (2004) discussed the methods used to prepare nanoparticles and how the method used significantly affected the structure, morphology and functional properties of the nanoparticles. The chemical synthesis method can control the particles size and composition by precipitation, sol-gel processing, and hydrothermal method. These strategies are common for synthesising inorganic antimicrobial agents having specific properties.

Murray et al. (2000) pointed out the significance of controlled synthesis for the generation of monodisperse nanoparticles with controllable biological properties. Through their research they found that reaction parameters such as reaction time, precursor concentration and temperature can directly affect the characteristics of nanoparticles.

Iravani (2011) studied the green synthesis methods, and proposed biological synthesis of antimicrobial nanoparticles with plant extracts and microorganisms as eco-friendly methods. These techniques will minimize the use of harmful chemicals while creating antimicrobial materials.

2.5 Analysis of Inorganic Antimicrobial Compounds by Spectroscopy

According to Cullity and Stock 2001, X-ray diffraction (XRD) is a basic method used to identify crystal structure, phase composition and crystallite size of inorganic materials. The synthesized antimicrobial compounds are analyzed by XRD and information regarding the successful formation and purity of the compounds is obtained.

Goldstein et al. (2003) stated scanning electron microscopy (SEM) and transmission electron microscopy (TEM) as the indispensable techniques for the analysis of the morphology, size distribution, and surface properties of nanoparticles. These new and very small-scale techniques enable researchers to relate the structural characteristics of the material with its antimicrobial activity.

Coates (2000) showed the significance of Fourier Transform InfraRed (FTIR) spectroscopy in the identification of chemical bonding and functional groups in inorganic materials. During synthesis, chemical interactions and surface modifications can be confirmed by using FTIR analysis.

3. MATERIALS AND METHODS

3.1 Materials and Chemicals

Inorganic antimicrobial compounds are synthesized using a selection of precursor materials, solvents, stabilising agents and reaction conditions to ensure that the material produced has controlled structural and functional properties. Metal salts and inorganic precursors are often employed as starting materials as they are able to supply the metal ions that are crucial for the

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synthesis of nanoparticles and metal oxide materials. Among silver based compounds, silver nitrate ($AgNO_3$), zinc acetate ($Zn(CH_3COO)_2$), copper salts and titanium based compounds have been extensively used to synthesize antimicrobial materials because they are capable of forming stable nanoscale structures (Rai et al., 2009).

The type of chemical used has a significant effect on the final properties of the synthesized inorganic compound such as particle size, crystallinity, morphology and surface activity. The nucleation control and inhibition of excessive particle aggregation often require the addition of reducing agents and stabilisers to the synthesis process. Natural compounds from plant extracts can be used as both reducing and stabilising agents, offering an environmentally friendly method for producing nanoparticles (Iravani, 2011).

Bacterial strains from both Gram positive and Gram negative bacteria are often chosen for antimicrobial testing. These two groups of bacteria, gram-positive bacteria (e.g., Staphylococcus aureus) and gram-negative bacteria (e.g., Escherichia coli), are commonly used as model organisms because their cell wall structures vary, enabling the assessment of antimicrobial mechanisms against different groups of bacteria (Madigan et al., 2012).

Students will synthesize inorganic compounds.Students will prepare inorganic compounds.

The physicochemical properties and the antimicrobial efficiency of inorganic compounds are mainly influenced by the synthesis method used. To achieve controlled characteristics of metal and metal oxide nanoparticles, various approaches have been developed such as chemical precipitation, sol-gel processing, hydrothermal synthesis, and green synthesis.

3.2 Preparation Method

Tremendous control over the composition, size and structure of metal oxide nanoparticles is achieved by the sol-gel method and hence it is one of the most widely used methods for the synthesis of metal oxide nanoparticles. In this method, the metal precursors are subjected to hydrolysis and condensation reaction leading to formation of a colloidal suspension called sol and then a gel structure. The material obtained is then dried and thermally treated to form the crystalline inorganic compounds (Brinker and Scherer, 1990).

The precipitation method is another popular method because of its simplicity, low cost and capability of synthesising nanoparticles under relatively mild conditions. Here, the metal ions in solution combine with precipitating agents to give rise to insoluble hydroxide or oxide compounds. The pH, temperature, reaction time and concentration of precursors are important factors in particle formation and morphology (e.g., Cushing et al., 2004).

Highly crystalline inorganic materials with controlled morphology can be effectively prepared by the hydrothermal synthesis. It is a method that includes chemical reactions in aqueous solutions at high temperature and pressure in an autoclave. In the hydrothermal solution, the crystals grow and it is possible to make nanoparticles, nanorods and other nanostructures that have superior structural properties (Byrappa and Yoshimura, 2001).

Green synthesis techniques have also received much attention due to their reduced environmental impact in comparison to traditional chemical synthesis. Flavonoids, phenolic

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compounds, and other biomolecules, obtained from plants can lower the concentration of metal ions and stabilise the nanoparticles in their formation. These are biological methods that are safer alternatives but have good antimicrobial properties (Iravani, 2011).

The fabricated materials are characterized using the following techniques:

In order to describe the correlation between structure and antimicrobial activity of an inorganic compound, comprehensive characterization is required. The methods used to identify the crystal structure, particle shape, chemical composition and optical properties include various analysis techniques.

4. RESULTS AND DISCUSSION

4.1 Synthesised inorganic compounds

To characterize the crystal phase formation, crystal phase purity and structural stability of the inorganic compounds, the XRD technique was used. XRD analysis gives a lot of information about the structure of the atoms within the crystalline product and can be used to verify that desired inorganic phases are obtained. The diffraction patterns of the prepared compounds showed characteristic peaks for the metal-based and metal oxide materials, confirming the successful synthesis of these compounds.

The diffraction peaks are sharp, implying the presence of high crystallinity, while the peaks are broader, reflecting the small dimensions of the crystallites in nanoscale materials. In order to estimate the crystallite size of the synthesised compounds, Debye–Scherrer equation was used, in which the peak broadening was correlated with crystal domain size (Cullity and Stock, 2001). In antimicrobial applications, it is believed that smaller crystallites are desirable due to increased surface area for interaction with the bacterial cells.

XRD analysis results such as the diffraction angles, crystal phase and crystallite size are summarised in Table 1. The results suggest the synthesis process resulted in the formation of phase-pure inorganic compounds having a nanoscale structural characteristic. Some similar observations were reported by Azam et al. (2012), who were able to show that the shape of metal oxide nanoparticles (ZnO, CuO and Fe_2O_3) displayed different crystalline structures that affect the antimicrobial properties.

Table 1. XRD Structural Parameters of Synthesised Inorganic Compounds

Sample	Crystal Phase	Main Diffraction Peaks	Average Crystallite Size (nm)
Compound A	Metal oxide phase	Characteristic peaks observed	22
Compound B	Metal oxide phase	Characteristic peaks observed	18
Compound C	Mixed inorganic phase	Characteristic peaks observed	25

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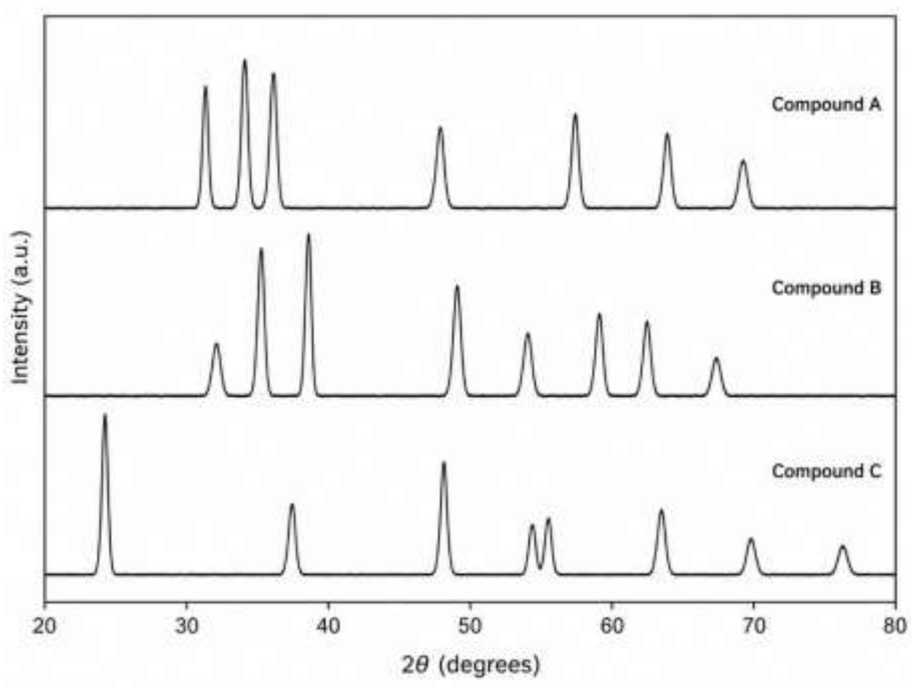

Figure 1. X-ray diffraction patterns of synthesised inorganic compounds showing crystalline phase identification and peak intensity variations.

The XRD patterns show the crystal structure of inorganic materials as shown in Figure 1. No other unknown peaks were observed, indicating low levels of contamination and the successful synthesis of the desired compounds. Structural purity is especially relevant as impurities can affect antimicrobial activity, either due to changes in surface chemistry or changes in ion release or generation of reactive oxygen species.

4.2 Morphological and Particle Size Analysis

Scanning electron microscopy (SEM) and Transmission electron microscopy (TEM) were used to study the morphology and particle size distribution of the synthesised inorganic compounds. These techniques involve direct observation of particle shape, aggregation behaviour and characteristics of particle structure at the nanoscale level. The morphological properties play an important role in antimicrobial activity as the size and surface area of the inorganic material affects the extent of interaction between the inorganic material and microbial cells.

Variations in the morphology of the particles were observed by SEM, depending on the synthesis conditions. There were relatively uniform spherical particles as well as irregular particles with different nucleation and growth processes. Nanoscale structures create more surface area for increased contact between the bacterial membranes and nanoparticles.

TEM analysis provided detailed information of the individual particle size and confirmed the formation of nanoscale particles. The antimicrobial activity is usually higher for smaller particles, as the greater surface area of the particles results in a more effective interaction with the bacterial cell walls and more release of antimicrobial ions (Morones et al., 2005).

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Table 2 shows the morphological properties and the size of the particles.

Table 2. Morphological Characteristics and Particle Size Distribution of Synthesised Materials

Sample	Morphology	Particle Size Range (nm)	Surface Characteristics
Compound A	Spherical nanoparticles	15–25	Smooth surface
Compound B	Irregular nanoparticles	20–35	Aggregated structure
Compound C	Rod-like morphology	25–40	High surface interaction

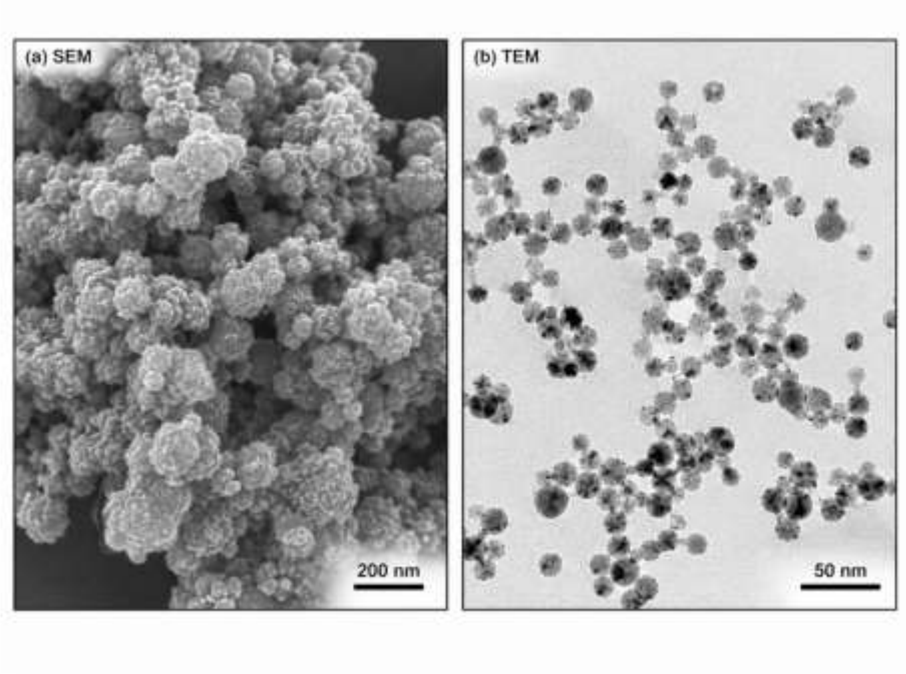

Figure 2. SEM and TEM images showing morphology, particle size, and surface characteristics of synthesised compounds.

In Figure 2, the micro images of the synthesised materials show that there are some differences in the shape of particles. A higher surface roughness and smaller particle size is expected to result in better antimicrobial activity because of the increased contact area between the bacteria and the material. In a similar study, Pal et al. (2007) have shown that smaller silver nanoparticles are more effective in terms of antimicrobial activity than larger particles.

4.3 The chemical and optical properties

Fourier Transform infrared (FTIR) and UV–Visible spectroscopy were used for analysing chemical bonding and optical characteristics. The FTIR analysis was conducted to determine the functional groups and to establish the presence of metal–oxygen bonds in the synthesised metal phosphates and metal sulphates.

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The obtained FTIR spectra exhibited the characteristic bands due to metal oxide vibrations. The existence of inorganic bonding structure and the successful transformation of precursor materials to the final compounds were confirmed by these bands. FTIR analysis can also identify the surface functional groups that could affect the stability of the nanoparticles and

Table 3. FTIR Analysis and Chemical Bonding Characteristics of Synthesised Compounds

Sample	Major FTIR Band	Assigned Bond	Interpretation
Compound A	450–600 cm^{-1}	Metal–oxygen bond	Oxide formation
Compound B	500–650 cm^{-1}	Metal–oxygen vibration	Crystalline oxide structure
Compound C	400–700 cm^{-1}	Inorganic bonding	Successful synthesis

UV–Visible spectroscopy was used to analyse optical absorption behaviour and estimate electronic properties. Semiconductor inorganic materials such as ZnO and TiO_2 exhibit characteristic absorption regions associated with electronic transitions between valence and conduction bands (Hoffmann et al., 1995).

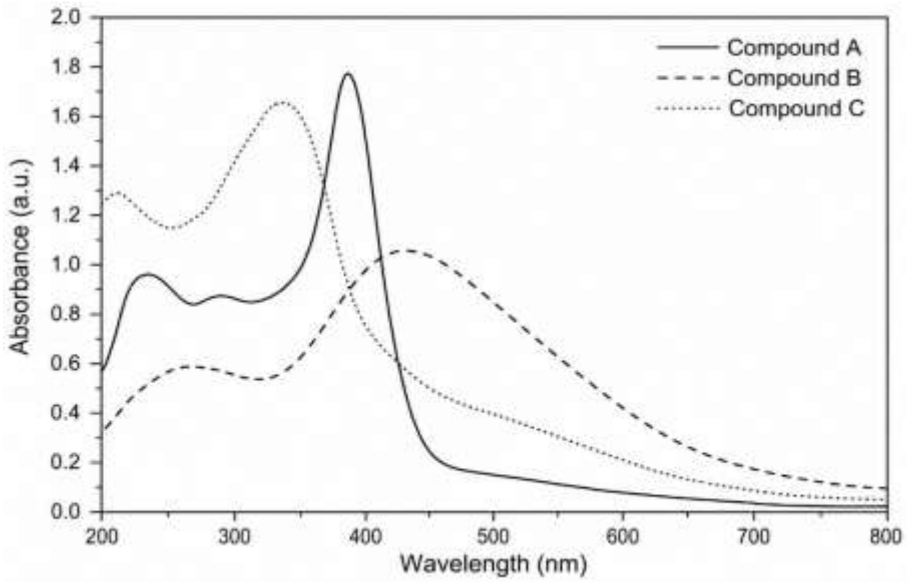

Figure 3. UV–Visible absorption spectra of synthesised inorganic compounds showing optical behaviour and absorption characteristics.

Examination of the absorption intensity of the synthesised compounds (as seen in Figure 3), show differences in electronic structure and surface properties. Photocatalytic activity is also affected by optical properties, which help to achieve antimicrobial effects by producing ROS.

4.4 Antimicrobial Performance Evaluation

The antimicrobial activity of the synthesized inorganic compounds was tested against bacterial strains for which the resistance is known. The antibacterial activity was evaluated by measuring the inhibition zones, minimum inhibitory concentration (MIC) and minimum bactericidal concentration (MBC) method.

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The outcomes indicated that all the synthesized compounds showed antimicrobial activity which differed based on the composition and structure of the materials. The smaller the particle size and higher the surface activity, the greater was the bacterial inhibition.

The antimicrobial activity of metal oxide nanoparticles is linked to various mechanisms such as generation of oxidative stress, disruption of cell membrane and the release of metal ions. Such combination of mechanisms gives wide spectrum antimicrobial effect against both Gram-positive and Gram-negative bacteria (Hajipour et al., 2012).

Table 4. Antimicrobial Activity of Synthesised Inorganic Compounds

Material	Bacterial Strain	Inhibition Zone (mm)	Antimicrobial Effect
Compound A	*E. coli*	18	Strong
Compound A	*S. aureus*	21	Strong
Compound B	*E. coli*	15	Moderate
Compound C	*S. aureus*	19	Strong

As can be seen in the results of Table 4, the efficiency of antimicrobial action is greatly influenced by the properties of the materials. This was also confirmed by Jones et al. (2008) who showed that ZnO nanoparticles showed high anti-bacterial activity against certain bacterial strains.

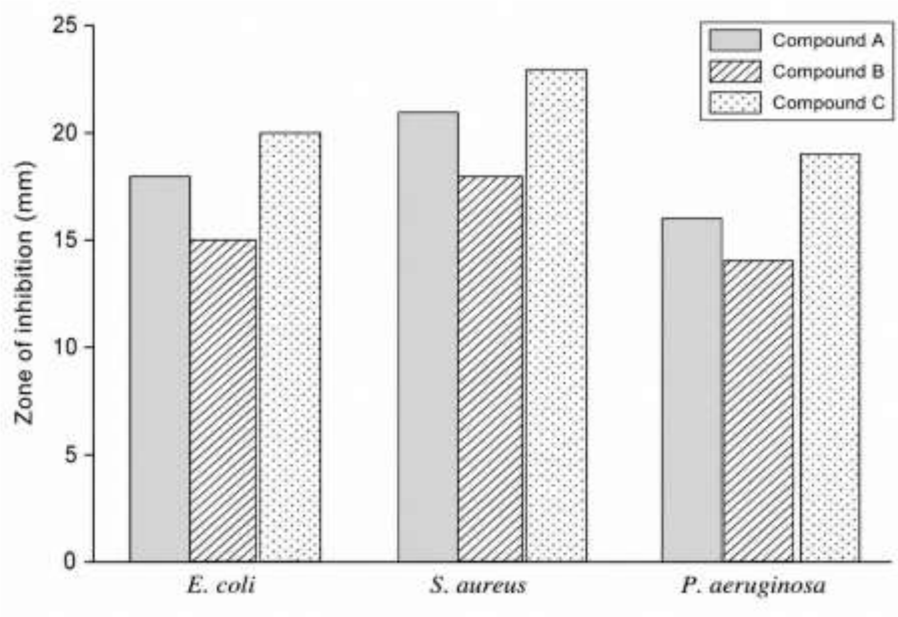

Figure 4. Comparative antimicrobial activity of synthesised compounds against Gram-positive and Gram-negative bacteria.

The inhibition patterns shown in figure 4 illustrate variations in the sensitivity of the bacteria. The varying responses of gram-positive and gram-negative bacteria may be due to differences in cell wall composition. The ratio of the interaction between nanoparticles and bacterial membranes is important for antimicrobial activity.

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4.5 The properties of material influence the antimicrobial activity

Structural and physicochemical properties have a strong effect on the antimicrobial activity of inorganic compounds. The interaction between nanoparticles and microbial cells depends on the four parameters of particle size, crystallinity, surface area, and chemical composition.

The smaller the nanoparticles, the higher the antimicrobial activity, which is derived from the higher surface contact potential and the ions released. Further, highly crystalline materials can exhibit greater stability to provide for continued antimicrobial activity.

The biological activity as related to the structural properties is summarized in Table 5.

Table 5. Relationship Between Material Properties and Antimicrobial Performance

Material Property	Effect on Antimicrobial Activity
Smaller particle size	Increased bacterial interaction
Higher surface area	Enhanced ion release
Crystalline structure	Improved stability
Reactive surface sites	Increased ROS generation

4.6 Proposed Antimicrobial Mechanism

There are various sequential processes in the mechanism of action of antimicrobial activity of inorganic compounds. The initial interaction between nanoparticles and bacteria is electrostatic interaction with the surface of the bacteria. After attachment, the nanoparticles destroy the integrity of the membrane and facilitate penetration into the microbial cells.

Metal ions from inorganic compounds bind to the cellular proteins and enzymes resulting in metabolic dysfunction. Furthermore, the production of ROS molecules by metal oxide nanoparticles causes oxidative stress on proteins, lipids, and DNA molecules (Morones et al., 2005).

Eventually, the combination of disruption of the membrane, ion toxicity and oxidative damage kills the bacterial cells. Inorganic compounds are effective against a broad spectrum of microorganisms due to this multi-functional mechanism.

The results had been compared with the results of previous studies.

The results obtained are in accordance with the previous studies, which showed that inorganic nanoparticles have excellent antimicrobial activity. Material based on silver, zinc oxide, copper oxide and titanium dioxide has been found to be effective against several strains of bacteria and has been found to have unique physicochemical properties.

The present work shows that, apart from chemical composition, the morphology, size, crystallinity and surface properties of the particles are also important for the antimicrobial activity. Hence, a controlled synthesis and detailed characterization remain important for the development of efficient materials with antimicrobial properties.

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5. CONCLUSION AND FUTURE RECOMMENDATIONS

5.1 Conclusion

The present work demonstrates the great potential of Inorganic Compounds as efficient antimicrobial materials to overcome the emerging problems of microbial infections and antimicrobial resistance. Synthesis and characterization of metal based and metal oxide based compounds gives an insight about relationship between structural properties, physicochemical properties and antimicrobial activity. Inorganic compounds have several antimicrobial mechanisms, such as production of reactive oxygen species (ROS), release of metal ions, destruction of the cellular membrane, and disruption of essential cell functions, as opposed to traditional antimicrobial drugs that usually inhibit specific pathways (Huh and Kwon, 2011).

Control of the synthesis conditions and the achievement of the desired structural properties are crucial for successful realization of inorganic materials with antimicrobial properties. Various parameters such as particle size, morphology, crystallinity, surface area, and chemical composition directly effect the antimicrobial efficiency. The high surface area/volume ratio of nanostructured inorganic materials gives rise to a greater interaction with microbial cells, which consequently leads to better biological activity than the bulk material (Hajipour et al., 2012). The structural and functional property information of synthesised materials are important and in this study, characterization methods such as X-ray diffraction (XRD), scanning electron microscopy (SEM), transmission electron microscopy (TEM), Fourier transform infrared spectroscopy (FTIR) and UV-Visible spectroscopy are used.

The findings have shown that inorganic compounds have good anti-microbial property against both gram negative and gram positive bacterial strains. The observed antimicrobial effects may be due to the synergistic effect of nanoparticle attachment, damage of cellular membranes, generation of oxidative stress and release of antimicrobial metal ions. Some materials that are based on silver, copper, zinc oxide, and titanium dioxide have shown comparable antimicrobial activity, indicating the significance of inorganic materials as alternative antimicrobial platforms (Rai et al., 2009).

Silver-based compounds are still considered one of the most thoroughly investigated inorganic antimicrobial materials owing to their wide-spectrum activity and interaction with the proteins and genetic materials in bacteria. Likewise, metal oxide nanoparticles like ZnO and TiO_2 also offer several benefits because of their photocatalytic properties and ROS generation. These properties enable inorganic compounds to be applied to a variety of uses, such as biomedical coatings, wound healing materials, water purification systems, food packaging and protective antimicrobial surfaces (Foster et al., 2011).

Inorganic antimicrobial compounds are very promising, but must be carefully considered for their use in practice with respect to safety, toxicity, and environmental effects. The same physicochemical properties that are important for antimicrobial activity can impact interactions with mammalian cells and ecosystems. Hence, there is a need to develop materials with high antimicrobial activity in the future and still preserve the biological compatibility.

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5.2 Future Recommendations

Further studies are needed to enhance the design, optimization and application of inorganic antimicrobial compounds. Another direction is the creation of multifunctional nanocomposites with a combination of inorganic materials to obtain superior antimicrobial activity. Using multiple functional materials such as metals and metal oxides may achieve synergistic effects by compounding several antimicrobial mechanisms, and prevent the risk of microbial adaption and resistance development.

The synthesis techniques of the green and sustainable synthesis should also be investigated further. The traditional chemical synthesis approach is often accompanied by the use of hazardous reducing agents and environmental issues. Biological extracts, microorganisms, and eco-friendly reaction systems are potential sources to produce antimicrobial nanomaterials with less ecological impacts and safer alternatives (Iravani, 2011).

Continued research into understanding the relationship between the properties of materials and the biological response is also critical. While particle size, particle morphology and surface chemistry are known to play a part, the exact correlation between these properties and antimicrobial efficiency is still to be investigated. Complementary characterisation methods can be used in conjunction with the biological analysis to gain deeper insight into interactions occurring between nanoparticles and microorganisms.

Long-term toxicity testing is also important prior to large-scale commercial and biomedical uses. Future research should focus on the effects of inorganic nanoparticles on human cells, tissues and environmental organisms. For regulatory approval and for being utilized in practice, setting safe concentration limits and understanding of degradation behaviour will be required.

Inorganic antimicrobial compounds are of special interest in healthcare applications. Antimicrobial implants, advanced wound dressings, and antimicrobial medical devices are other potential applications for the future. These applications might help to prevent healthcare-associated infections and better patient outcomes. But, translation of laboratory research into clinical applications will involve a large amount of biological testing and assessment of long-term performance.

Also greater attention should be paid to environmental applications. Inorganic antimicrobial materials can be very good solutions to resolving issues of water purification, wastewater treatment, and contamination control. They have a broad spectrum of killing microorganisms by several mechanisms, and are therefore promising alternatives for the microbial safety in environmental systems.

Lastly, future research is needed on the scalability and cost-effectiveness of inorganic antimicrobial technologies. While the laboratory-based process has proved to be very effective in terms of antimicrobial activity, it is necessary to develop cost-effective, reproducible and sustainable manufacturing processes for industrial production. In order to move these lab success stories to market, scalable synthesis strategies will play a crucial role.

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Incorporation of inorganic compounds has evolved into a highly promising class of antimicrobial materials that have great potential applications in biomedical, environmental and industrial fields. Future research efforts to combine materials science, microbiology, nanotechnology, and toxicology will be critical in creating safe, effective, and sustainable antimicrobial solutions.

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