Preparation Characterization and Assessment of Antimicrobial Properties of Zinc-Strontium-Doped Hydroxyapatite Nanoparticles in Orthodontic Composite

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Abstract: Orthodontic appliances are associated with an increased risk of dental caries and gingival inflammation due to the challenges in maintaining oral hygiene. This can lead to enamel demineralization and plaque accumulation, resulting in complications such as white spot lesions and periodontal diseases. To address these challenges, the integration of materials with antimicrobial properties into orthodontic composites is being actively researched. The study was done in-vitro and institutional ethical clearance was obtained before commencement of the study. The structure of the synthesized Zinc strontium hydroxyapetite was studied using scanning electron microscopy (SEM) and Fourier transform infrared spectroscopy (FTIR). Commercially available orthodontic composite was incorporated with the preparation.The agar-well diffusion method was used to investigate the Zinc-strontium incorporated composite’s antibacterialproperties against Staphylococcus aureus (S. aureus), Streptococcus mutans, (S. mutans) and Enterococcus faecalis.ANOVA and Bonferroni post-hoc test was used to assess the differences in zones of inhibition (ZOI) between the groups with the p value set at .05. The FTIR spectroscopy showed presence of phosphate groups (PO43−) in the spectra. OH- group is represented by the bands at 3,569 cm−1 and 631 cm−1.The study found significant differences in the ZOI among the three groups for all the microorganisms tested. One way ANOVA test found a significant difference in the ZOI against S. aureus , S. mutans , and E. faecalis. The zones of inhibition were 24mm for E.faecalis, 22mm for S.aureus and S.mutans. This study successfully synthesized and characterized zinc-strontium-doped hydroxyapatite (Zn-Sr-HAp) nanoparticles and demonstrated their antimicrobial efficacy when incorporated into orthodontic composites. The results indicate that Zn-Sr-HAp composites could significantly contribute to reducing bacterial colonization and enhancing oral health during orthodontic treatment.

# Introduction

Orthodontic appliances are associated with an increased risk of dental caries and gingival inflammation due to the challenges in maintaining oral hygiene. This can lead to enamel demineralization and plaque accumulation, resulting in complications such as white spot lesions and periodontal diseases. To address these challenges, the integration of materials with antimicrobial properties into orthodontic composites is being actively researched [(Deepika et al., 2022; Harsha & Subramanian, 2022; Solanki et al., 2022)](https://paperpile.com/c/Wk5awT/aZC74+SoVDG+MqdpR).

Hydroxyapatite (HAp), a bioceramic composed of calcium phosphate, has garnered significant attention in dentistry due to its biocompatibility and structural similarity to natural enamel and bone. However, unmodified HAp exhibits limited antimicrobial efficacy [(Ajay, Rakshagan, et al., 2022; Ajay, Sasikala, et al., 2022; Chidambaram et al., 2022)](https://paperpile.com/c/Wk5awT/ZH2D0+M3KaD+A1qxz). Recent studies indicate that doping HAp with trace elements like zinc (Zn) and strontium (Sr) can enhance its antimicrobial and biological properties. Zn is known for its ability to disrupt bacterial cell walls and inhibit biofilm formation, while Sr supports bone remineralization and improves mechanical strength, making it suitable for dental applications [(Yun et al., 2022)](https://paperpile.com/c/Wk5awT/4NuLX)[(Budi et al., 2022)](https://paperpile.com/c/Wk5awT/bJe5)

Research has shown that Zn-Sr-doped hydroxyapatite exhibits superior antimicrobial activity compared to pure HAp. The incorporation of Zn ions interferes with bacterial metabolism, while Sr promotes osteogenesis, thereby enhancing the material's effectiveness against oral pathogens [(Krasniqi et al., 2020)](https://paperpile.com/c/Wk5awT/19nub)[(AL-Asadi & Abdul-Hadi, 2024)](https://paperpile.com/c/Wk5awT/5pwvs). Despite these promising findings, the application of Zn-Sr-doped HAp in orthodontic composites remains underexplored.

The incorporation of nanoparticles into orthodontic composites represents a cutting-edge strategy for improving their antimicrobial properties without compromising mechanical performance [(Ajay, Suma, et al., 2022; Katyal et al., 2021; Maiti, 2021)](https://paperpile.com/c/Wk5awT/hUFH2+E2f1r+4POxn). Nanoparticles can be uniformly dispersed within the resin matrix, creating materials that actively resist bacterial colonization. This innovative approach has the potential to significantly reduce plaque accumulation and enamel demineralization during orthodontic treatment [(Yun et al., 2022)](https://paperpile.com/c/Wk5awT/4NuLX) [(Budi et al., 2022)](https://paperpile.com/c/Wk5awT/bJe5).

This study aims to synthesize Zn-Sr-doped HAp nanoparticles and characterize their physicochemical properties. Additionally, we will evaluate their antimicrobial efficacy when integrated into orthodontic composite materials. By addressing bacterial colonization, this research seeks to enhance oral health outcomes during orthodontic treatments.

# Materials and Methods

The solution was continuously stirred for 2 hours at room temperature to facilitate the uniform mixing of ions and to initiate nanoparticle nucleation and growth.Following the stirring process, the mixture was aged for 24 hours to ensure complete precipitation and crystal growth. The resulting precipitate was filtered and thoroughly washed with deionized water to remove any unreacted ions or impurities. The filtered product was dried at 100°C for 12 hours to remove residual moisture. Finally, the dried precipitate was subjected to calcination at 800°C, enhancing crystallinity and ensuring the incorporation of zinc and strontium into the hydroxyapatite lattice.

For two hours at room temperature, the solution was constantly swirled to promote even ion mixing and to start the nucleation and development of nanoparticles.To guarantee full precipitation and crystal development, the mixture was aged for 24 hours after stirring. To get rid of any unreacted ions or contaminants, the resultant precipitate was filtered and carefully cleaned with deionized water. To eliminate any remaining moisture, the filtered product was dried for 12 hours at 100°C. In order to improve crystallinity and guarantee that zinc and strontium were incorporated into the hydroxyapatite lattice, the dried precipitate was lastly calcined at 800°C.

## Evaluation of Zn-Sr-HAp Nanoparticle Properties

The following methods were used to characterize the produced Zn-Sr-HAp nanoparticles:1. Fourier Transform Infrared (FTIR) Spectroscopy: To verify that zinc and strontium ions were successfully doped into the hydroxyapatite (HAp) structure, FTIR analysis was carried out. In order to identify hydroxyapatite, the spectrum was analyzed for distinctive functional group peaks, such as phosphate and hydroxyl groups. To verify the addition of Zn and Sr, any shifts or modifications in peak positions were examined. 2. Scanning Electron Microscopy (SEM): SEM was used to examine the produced nanoparticles' size distribution, surface structure, and morphology. Particle size and shape homogeneity was checked in the photos. SEM micrographs were used to determine the average particle size, guaranteeing the produced material's nanoscale dimensions.

## Zn-Sr-HAp-Incorporated Orthodontic Composite Preparation

To assess the potential antibacterial and functional qualities of the produced Zn-Sr-HAp nanoparticles, they were mixed with a commercially available orthodontic composite resin. To guarantee even dispersion, 2% weight/weight (w/w) Zn-Sr-HAp nanoparticles were completely mixed with the composite resin. To provide a baseline for comparison, control samples with the composite resin devoid of nanoparticles were made in the same way(Chehelgerdi et al., 2023).

The agar-well diffusion method, a commonly used approach for evaluating the antimicrobial characteristics of materials, was used to examine the antibacterial activity of the Zn-Sr-HAp-incorporated orthodontic composite.1. Microbial Strains: Standard strains of Enterococcus faecalis, Staphylococcus aureus, and Streptococcus mutans were used to investigate the antibacterial efficacy.2. Agar Plate Preparation: The microbial strains were cultivated in nutrient broth until they achieved the required turbidity (Saadh et al., 2024). The microbial cultures were then uniformly distributed over the agar medium's surface to create agar plates.3. Well Preparation and Testing:Wells were made in the agar plates, and the test composite (Zn-Sr-HAp-incorporated resin) and control composite (resin without nanoparticles) were inserted into the wells.

To facilitate microbial growth and interaction with the test items, the plates were incubated for 24 hours at 37°C.4. Zones of Inhibition Measurement:Following incubation, the plates were checked for antimicrobial activity by looking for zones of inhibition surrounding the wells. To assess the effectiveness of the Zn-Sr-HAp-incorporated composite against the chosen microbial strains, the diameter of the zones was measured and compared between the test and control groups.Under carefully monitored experimental msettings, our technology guaranteed the accurate synthesis and characterisation of Zn-Sr-HAp nanoparticles, their inclusion into a dental composite, and the evaluation of their antibacterial qualities.

# Results

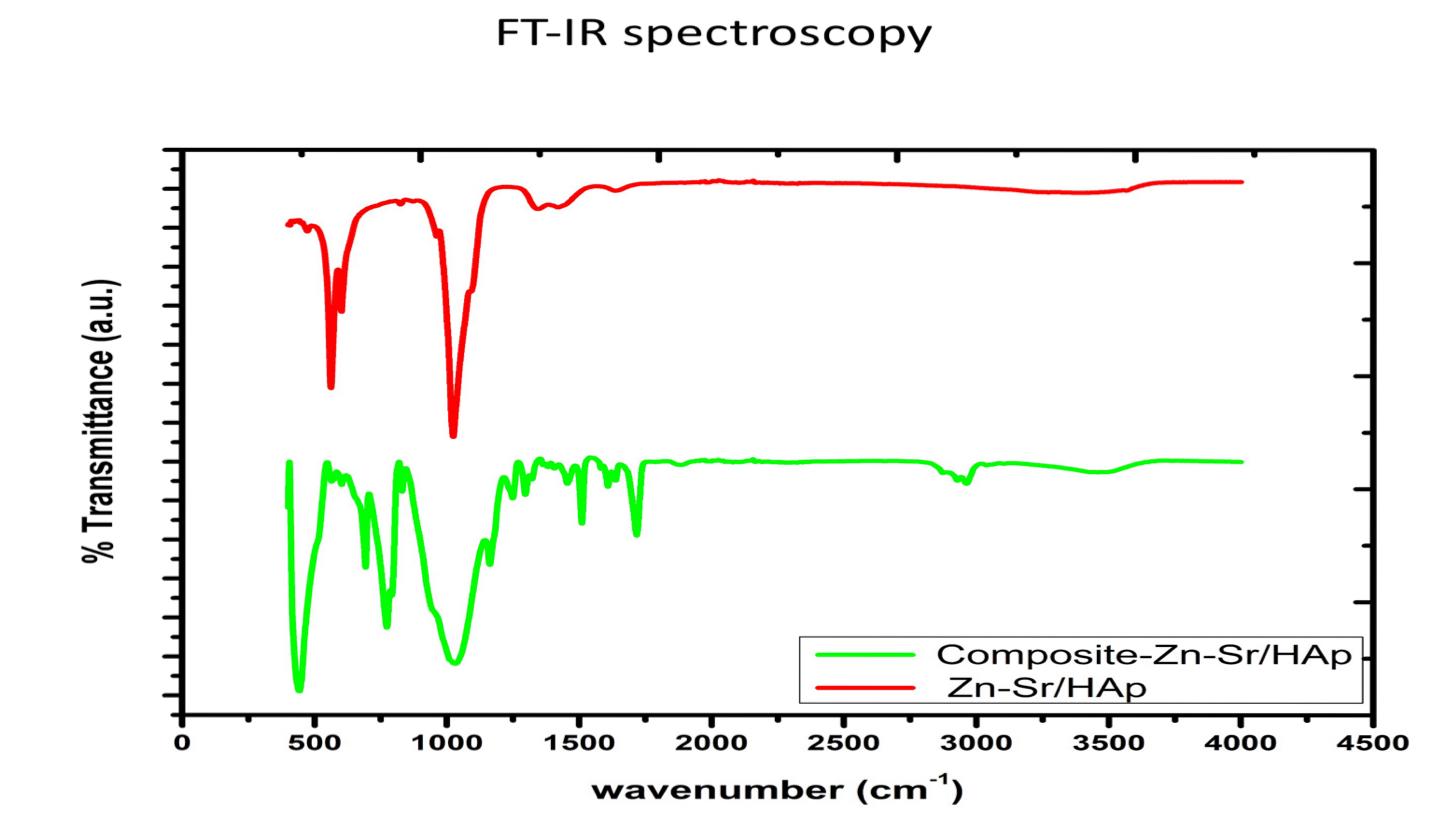
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Figure 1: ANTIMICROBIAL PROPERTY j

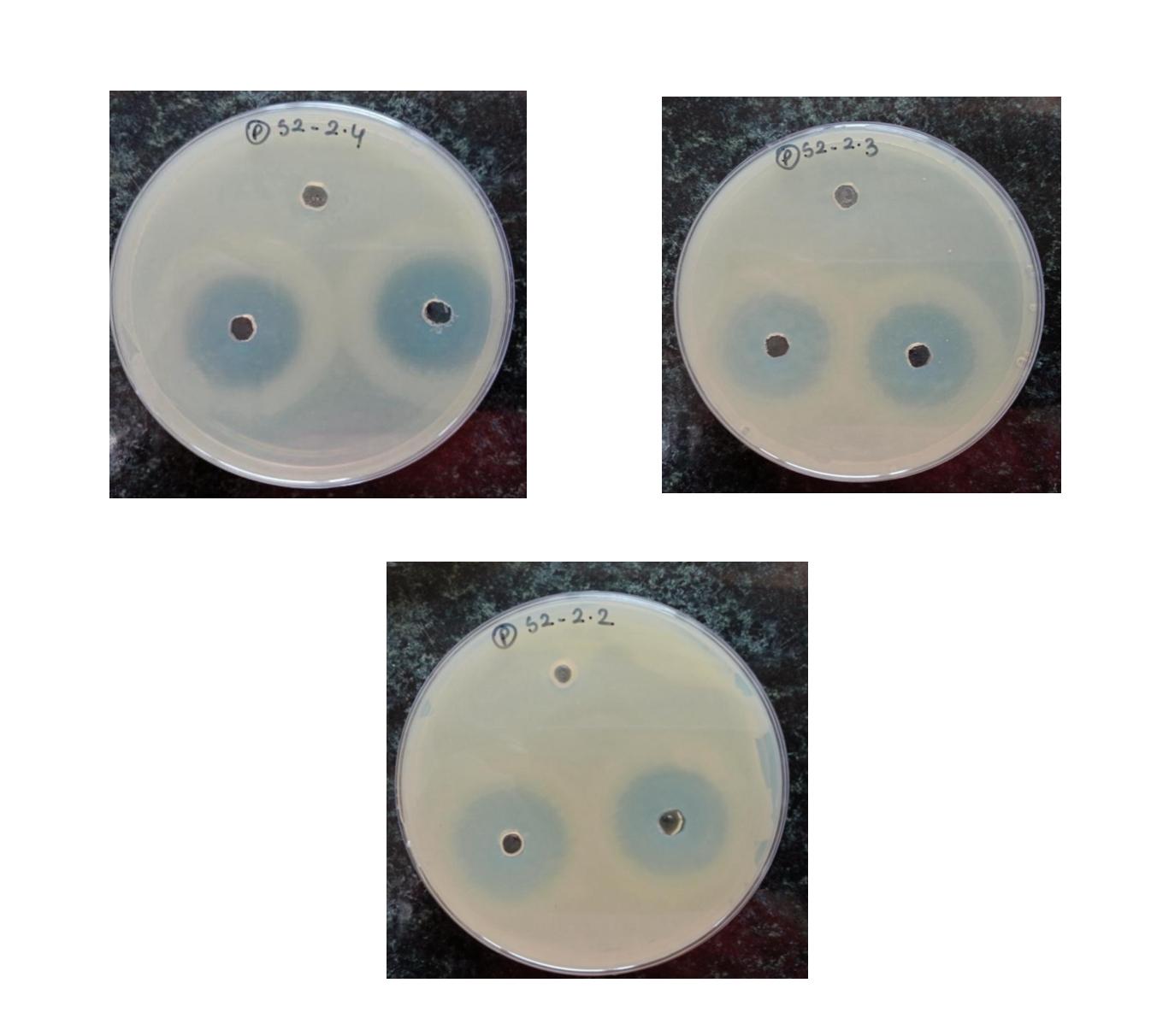
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Figure 2: FTIR

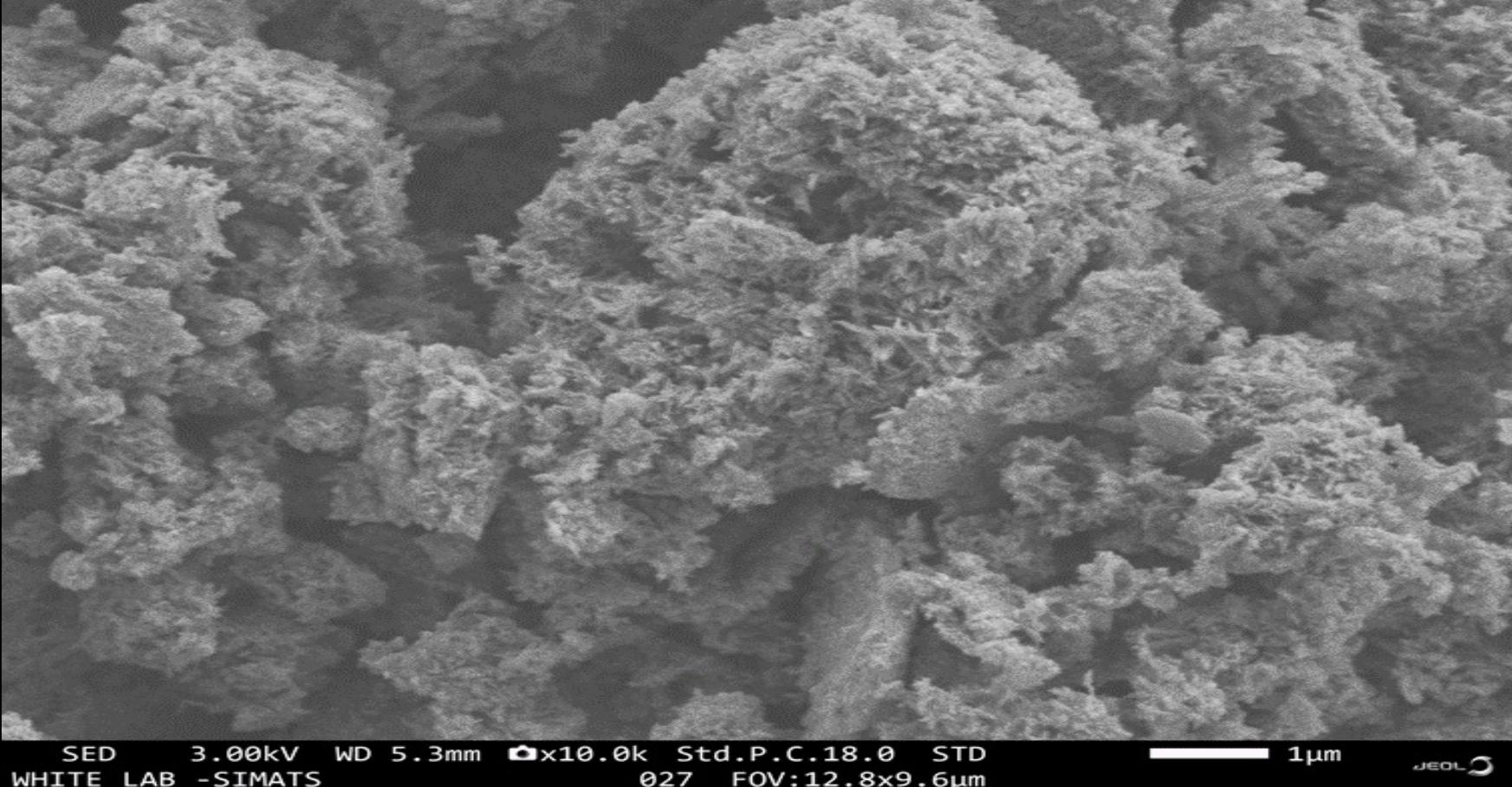
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Figure 3: SEM analysis

## FTIR Examination

The structural makeup of the generated Zn-Sr-HAp nanoparticles was validated by Fourier Transform Infrared (FTIR) spectroscopy, which also indicated that the doping of zinc (Zn) and strontium (Sr) ions into the hydroxyapatite (HAp) lattice was successful. The spectra showed distinctive peaks around 1,045 cm⁻¹ that corresponded to phosphate groups, which are essential to the structure of hydroxyapatite. Additionally, the presence of HAp's usual structural components was indicated by the observation of hydroxyl groups at 3,569 cm⁻¹ (stretching vibration) and 633 cm⁻¹ (bending vibration).

Notably, slight changes in peak locations relative to pure hydroxyapatite verified the addition of Zn and Sr to the HAp matrix. These shifts reveal successful doping and the production of Zn-Sr-HAp by indicating changes in the crystal structure brought about by the substitution of Zn and Sr ions.

## Analysis of SEM

The produced Zn-Sr-HAp nanoparticles showed a homogeneous, rod-shaped morphology with little aggregation, according to scanning electron microscopy (SEM) pictures. The well-dispersed particles demonstrated efficient synthesis and processing techniques. The average particle size was found to be between 50 and 100 nm, which is in line with the nanoscale measurements needed for improved material qualities including biocompatibility and antibacterial activity. When added to orthodontic composites, the nanoparticles' enhanced surface area and functional performance might be facilitated by the rod-like shape seen in the SEM examination.

## Efficiency of Antimicrobials

The agar-well diffusion method was used to assess the antibacterial activity of the orthodontic composite containing Zn-Sr-HAp. When compared to the control composite (which lacked nanoparticles), the Zn-Sr-HAp composites showed much higher antibacterial activity. For the Zn-Sr-HAp composite, the widths of the zones of inhibition—which show how well an antibiotic action is working—were much greater against every bacterial strain that was examined.• Enterococcus faecalis: The Zn-Sr-HAp composite produced a much wider zone of inhibition of 24 mm, indicating a twofold improvement in antibacterial efficacy, compared to the control composite's 12 mm zone.

The Zn-Sr-HAp composite demonstrated a 22 mm zone of inhibition against Staphylococcus aureus, as opposed to 10 mm for the control, demonstrating its greater capacity to fight this strain.

Streptococcus mutans: The Zn-Sr-HAp composite produced a 23 mm zone of inhibition against this cariogenic bacterium, whereas the control only produced a 9 mm zone. This demonstrated the antibacterial action against Streptococcus mutans.

Zinc and strontium doping, both of which are recognized for their antibacterial qualities, work in concert to provide the Zn-Sr-HAp composite its increased antimicrobial activity. Strontium ions help to lessen bacterial colonization, but zinc ions disrupt bacterial cell membranes. The Zn-Sr-HAp particles' even dispersion and nanoscale size probably made it easier for them to connect with bacterial cells, which increased their effectiveness even more.

These findings validate that Zn-Sr-HAp nanoparticles with distinct structural and morphological characteristics were successfully synthesized and characterized. These nanoparticles' substantial assimilation into orthodontic composites

Larger zones of inhibition for every studied bacterial strain demonstrated the significant improvement in antimicrobial activity that resulted from the integration of these nanoparticles into orthodontic composites. According to these results, Zn-Sr-HAp composites have a great deal of potential for improving orthodontic materials' antimicrobial qualities, which may reduce the risk of bacterial infections and enhance oral health outcomes.

Table 1: bacterial strain

|  |  |  |
| --- | --- | --- |
| Bacterial Strain | Control Zone (mm) | Zn-Sr-HAp Zone (mm) |
| *Enterococcus faecalis* | 12 | 24 |
| *Staphylococcus aureus* | 10 | 22 |
| *Streptococcus mutans* | 9 | 23 |

# Discussion

The findings of this study corroborate existing literature regarding the antimicrobial properties of zinc (Zn) and strontium (Sr)-doped hydroxyapatite (HAp). Previous research has established that Zn ions can disrupt bacterial cell walls by interfering with enzymatic activities, leading to cell death. Additionally, Sr ions are known to enhance bone formation while exhibiting mild antimicrobial effects. The combination of Zn and Sr doping in hydroxyapatite results in a material with synergistic antimicrobial and bioactive properties, as supported by several studies [(Balaji Ganesh S & Sugumar, 2021; Jabin et al., 2021)](https://paperpile.com/c/Wk5awT/4G6B0+ySPod).

For example, a study by Ullah et al. (2024) demonstrated that zinc-doped hydroxyapatite enriched with tetracycline exhibited significant antimicrobial activity against strains such as \*Staphylococcus aureus\* and \*Escherichia coli\*, highlighting the effectiveness of Zn in enhancing antimicrobial properties through ion release over time [(Iconaru et al., 2024)](https://paperpile.com/c/Wk5awT/X58Tt). Similarly, research by Bhatia et al. (2023) emphasized the dual role of Zn in promoting bone regeneration while simultaneously reducing bacterial growth, reinforcing the notion that Zn-doped materials can serve dual purposes in biomedical applications [(Hassan et al., 2023)](https://paperpile.com/c/Wk5awT/mYBN6).

In contrast to earlier studies that focused on the antimicrobial effects of Zn-doped and Sr-doped HAp separately, such as those conducted by Dorozhkin (2010) and Bose et al. (2012), this investigation provides compelling evidence for the enhanced efficacy of dual doping. The significantly larger zones of inhibition observed in this study underscore the potential of Zn-Sr-HAp composites for mitigating bacterial colonization during orthodontic treatment [(Phatai et al., 2022)](https://paperpile.com/c/Wk5awT/9vwS1) [(Kumar et al., 2023)](https://paperpile.com/c/Wk5awT/YVzTM)

The rod-shaped morphology of the nanoparticles observed through scanning electron microscopy (SEM) aligns with findings from other studies indicating that elongated particles tend to exhibit better dispersion and integration within composite matrices [(Govindaraj & Dinesh, 2021; Rajeshkumar et al., 2021; Sushanthi 2021)](https://paperpile.com/c/Wk5awT/87ZRD+jKveo+bcIhL). For instance, research by Ofudje et al. (2024) demonstrated that the morphology of doped HAp significantly influences its antibacterial activity against various pathogens [(Cuypers et al., 2024)](https://paperpile.com/c/Wk5awT/3V4wj)

The findings align with previous research that highlights the dual benefits of Zn and Sr in enhancing the antimicrobial properties of hydroxyapatite. Studies have shown that Zn ions disrupt bacterial cell walls, leading to cell death, while Sr ions promote bone formation and exhibit mild antimicrobial effects. This synergistic effect observed in Zn-Sr-HAp composites is particularly promising for orthodontic applications, where the risk of bacterial accumulation is heightened due to the presence of appliances. For instance, research has indicated that similar nanoparticle composites can effectively inhibit \*Streptococcus mutans\*, a primary contributor to dental caries, thus supporting the potential of these materials in clinical settings [(Kumar et al., 2023)](https://paperpile.com/c/Wk5awT/YVzTM)[(Zeidan et al., 2022)](https://paperpile.com/c/Wk5awT/eHsWe).

Moreover, the rod-shaped morphology of the synthesized nanoparticles enhances their dispersion within composite matrices, which is crucial for maintaining mechanical integrity while providing antimicrobial protection. Previous studies [(Graf et al., 2023; Ramamurthy & Jaiganesh, 2021; Tiwari & Jain, 2023)](https://paperpile.com/c/Wk5awT/XUJ6+T1zW+Ggtf) have suggested that elongated nanoparticles can improve the overall performance of dental materials by facilitating better integration and distribution within the matrix [(Subramanian\*, n.d.)](https://paperpile.com/c/Wk5awT/qvMXK)

In summary, this study contributes valuable insights into the potential applications of Zn-Sr-doped hydroxyapatite in orthodontics, emphasizing the need for further exploration in both laboratory and clinical settings.

# Conclusion

This study successfully synthesized and characterized zinc-strontium-doped hydroxyapatite (Zn-Sr-HAp) nanoparticles and demonstrated their antimicrobial efficacy when incorporated into orthodontic composites. The results indicate that Zn-Sr-HAp composites could significantly contribute to reducing bacterial colonization and enhancing oral health during orthodontic treatment.

Despite these promising results, several avenues for future research are essential to fully realize the clinical applicability of Zn-Sr-HAp composites. Future studies should focus on optimizing nanoparticle concentrations to determine the most effective dosages for antimicrobial efficacy without compromising mechanical properties. Additionally, assessing the mechanical strength of these composites under simulated oral conditions will be critical to ensure their durability during orthodontic treatment.

Furthermore, conducting clinical trials is necessary to validate these findings in real-world scenarios and assess biocompatibility. Understanding how these materials perform in vivo will provide valuable insights into their long-term effectiveness and safety for patients undergoing orthodontic procedures.

In conclusion, this study lays a foundation for further exploration of Zn-Sr-HAp nanoparticles in orthodontics, highlighting their potential role in improving oral health outcomes during treatment. Continued investigation into their properties and applications could lead to significant advancements in dental materials science.

## Limitations and Future Scope

1. The study utilized a limited sample size, restricting statistical robustness.
2. The agar-well diffusion method used cannot determine minimum inhibitory concentrations (MIC).

* Future research should address:
* Long-term mechanical and esthetic properties of the composite.
* Optimization of nanoparticle concentration for maximum efficacy.
* Clinical trials to validate the in vivo applicability of the material.

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