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Green Synthesis, Characterization, and Antimicrobial Efficacy of *Maerua oblongifolia* Nanoparticles: A Study on Enhanced Antibacterial Potential

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Abstract

This study investigates the antimicrobial and anti-inflammatory potential of herbal nanoparticles derived from *Maerua oblongifolia*, a plant known for its medicinal properties. Nanoparticles were synthesized using the leaf extract and characterized for size, stability, and drug entrapment efficiency. The synthesized nanoparticles exhibited an average particle size of 128.5 nm as determined by PSA (Particle Size Analyzer) and showed a zeta potential of -28.7 mV, confirming their stability. Drug entrapment efficiency was found to be 78.4%, indicating efficient loading of the bioactive compounds from *Maerua oblongifolia*. Antimicrobial activity was evaluated against common pathogenic strains, including Escherichia coli and Staphylococcus aureus, with an observed inhibition zone of 15.2 mm and 13.4 mm, respectively. These findings suggest that *Maerua oblongifolia* nanoparticles possess strong antimicrobial properties, making them a promising candidate for further pharmaceutical applications.

1. Introduction

Nanotechnology has emerged as a powerful tool in enhancing the therapeutic potential of herbal medicines by improving bioavailability, stability, and targeted delivery of active compounds. Herbal nanoparticles have attracted significant interest due to their ability to encapsulate bioactive molecules, protect them from degradation, and provide controlled release, thereby enhancing the efficacy of traditional herbal medicines. One such medicinal plant, *Maerua oblongifolia*, commonly known as Indian caper, has been widely used in traditional medicine for its anti-inflammatory, antimicrobial, and antioxidant properties. Despite its vast ethnopharmacological applications, the full potential of *M. oblongifolia* in modern medicine remains underexplored, particularly in the form of nanoformulations.

The roots and leaves of *Maerua oblongifolia* are rich in bioactive compounds such as flavonoids, saponins, and alkaloids, which have been reported to exhibit significant biological activities. However, like many herbal remedies, these compounds often suffer from poor solubility and bioavailability, limiting their therapeutic efficacy. Nanoparticles offer a promising solution to these challenges by increasing the surface area, enhancing solubility, and facilitating the controlled release of the bioactive components, thus improving their pharmacokinetic properties (Kashyap et al., 2019; Yadav et al., 2020).

The primary aim of this study is to synthesize and evaluate the antimicrobial and anti-inflammatory potential of herbal nanoparticles derived from *Maerua oblongifolia*. The nanoparticles were prepared using the plant's leaf extract and characterized using Particle Size Analyzer (PSA) and zeta potential measurement for their size distribution and stability. Additionally, the drug entrapment efficiency of the nanoparticles was assessed to determine the encapsulation of active compounds. The antimicrobial activity of the formulated nanoparticles was tested against common bacterial strains, and their anti-inflammatory potential was evaluated using standard in vivo models.

Previous studies have highlighted the antimicrobial activity of *M. oblongifolia*, but the incorporation of its bioactive compounds into a nanoparticle delivery system is expected to significantly enhance its efficacy (Singh et al., 2021; Thomas et al., 2022). This study aims to bridge the gap by providing a comprehensive analysis of *Maerua oblongifolia* nanoparticles, offering valuable insights into their potential application in treating infections and inflammatory conditions. The results of this research could pave the way for developing novel herbal-based nanoformulations with enhanced therapeutic efficacy.

2. Materials and Methods:

Plant Material and Extract Preparation

Fresh leaves of *Maerua oblongifolia* were collected from a local area and authenticated by a botanist. The leaves were thoroughly washed, air-dried at room temperature, and ground into a fine powder. For the extract preparation, 20 g of powdered leaves were soaked in 200 mL of ethanol for 72 hours, followed by filtration through Whatman filter paper No. 1. The filtrate was then concentrated using a rotary evaporator at 40°C to obtain a thick viscous extract, which was stored at 4°C for further use (Bala et al., 2015).

Synthesis of Nanoparticles

Herbal nanoparticles were synthesized using a green synthesis approach. The prepared extract (50 mg) was dissolved in distilled water and sonicated for 30 minutes to ensure homogeneity. The mixture was then added dropwise to a solution of 0.1% polyvinyl alcohol (PVA) while stirring at 800 rpm. The nanoparticle formation occurred via the solvent evaporation technique, where the mixture was stirred continuously for 4 hours. After nanoparticle formation, the solution was centrifuged at 15,000 rpm for 30 minutes, and the supernatant was discarded. The pellet was washed thrice with distilled water and freeze-dried to obtain the nanoparticles (Nasrollahzadeh et al., 2018).

Characterization of Nanoparticles

The synthesized nanoparticles were characterized for particle size, zeta potential, and drug entrapment efficiency. Particle size was measured using a Particle Size Analyzer (PSA) (Malvern Instruments, UK), while the surface charge (zeta potential) was determined using a Zetasizer Nano ZS (Malvern Instruments, UK). For drug entrapment efficiency, a known amount of nanoparticles was dissolved in ethanol, and the amount of entrapped bioactive compound was quantified using UV-Vis spectrophotometry at a wavelength specific to the extract (Tavakoli et al., 2017). The drug entrapment efficiency (DEE) was calculated using the formula:

DEE(%)=Amount of drug in nanoparticlesTotal amount of drug added×100DEE (\%) = \frac{\text{Amount of drug in nanoparticles}}{\text{Total amount of drug added}} \times 100DEE(%)=Total amount of drug addedAmount of drug in nanoparticles×100

Fourier-Transform Infrared Spectroscopy (FTIR) Analysis

FTIR analysis was performed to identify the functional groups present in the Maerua oblongifolia leaf extract and its corresponding nanoparticles. The analysis helps confirm the interaction between bioactive compounds and the nanoparticle matrix, ensuring successful encapsulation.

For the FTIR analysis, the dried powder of the Maerua oblongifolia extract and synthesized nanoparticles were mixed with potassium bromide (KBr) in a 1:100 ratio and pressed into pellets using a hydraulic press. The spectra were recorded using an FTIR spectrometer (PerkinElmer, USA) in the range of 4000–400 cm^{-1} at a resolution of 4 cm^{-1}. The characteristic peaks corresponding to various functional groups, such as hydroxyl, carboxyl, and alkene groups, were identified and compared between the extract and nanoparticles to confirm the successful synthesis and encapsulation of the bioactive compounds within the nanoparticles (Nasrollahzadeh et al., 2018; Tavakoli et al., 2017).

The FTIR spectra of the Maerua oblongifolia extract showed prominent peaks at 3412 cm^{-1} (O–H stretching), 2924 cm^{-1} (C–H stretching), and 1650 cm^{-1} (C=O stretching), indicating the presence of polyphenols, flavonoids, and other bioactive compounds. After nanoparticle synthesis, the peaks slightly shifted and broadened, particularly in the range of 1600–1500 cm^{-1}, suggesting successful interaction between the plant compounds and the polymer matrix used for nanoparticle formulation (Singh et al., 2021; Sukanya et al., 2015).

Antimicrobial Activity

The antimicrobial activity of the nanoparticles was evaluated using the agar well diffusion method. Pathogenic bacterial strains, including *Escherichia coli* and *Staphylococcus aureus*, were cultured in Mueller-Hinton agar plates. Wells were made in the agar plates, and 50 µL of the nanoparticle suspension (1 mg/mL) was added to each well. The plates were incubated at 37°C for 24 hours, and the zone of inhibition was measured in millimeters (mm) (Sukanya et al., 2015).

3. Results:

Particle Size and Zeta Potential

The synthesized nanoparticles were characterized using Particle Size Analyzer (PSA) and Zetasizer for size distribution and stability. The average particle size of the *Maerua oblongifolia* nanoparticles was found to be 128.5 nm, with a polydispersity index (PDI) of 0.267, indicating a relatively narrow size distribution. The zeta potential of the nanoparticles was measured as -28.7 mV, which suggests that the particles have sufficient electrostatic stability, preventing aggregation in suspension. These results are consistent with other studies where herbal nanoparticles showed similar particle size and zeta potential values, enhancing stability and bioavailability (Bala et al., 2015; Tavakoli et al., 2017).

Drug Entrapment Efficiency

The drug entrapment efficiency (DEE) of the nanoparticles was assessed by quantifying the number of bioactive compounds encapsulated within the nanoparticles. The DEE was calculated to be 78.4%, indicating an efficient encapsulation of *Maerua oblongifolia*'s bioactive constituents. This high encapsulation efficiency is critical for ensuring a sustained and controlled release of the active compounds, thereby enhancing the therapeutic potential of the nanoparticles. Previous studies have shown that herbal nanoparticles can achieve entrapment efficiencies ranging from 70% to 85%, depending on the method of synthesis and the nature of the plant extract (Nasrollahzadeh et al., 2018; Singh et al., 2021).

FTIR Analysis

The Fourier-Transform Infrared Spectroscopy (FTIR) analysis was conducted to identify the functional groups present in both the Maerua oblongifolia leaf extract and the synthesized nanoparticles, confirming the successful interaction and encapsulation of the bioactive compounds within the nanoparticle matrix.

FTIR Spectrum of Maerua oblongifolia Extract

The FTIR spectrum of the Maerua oblongifolia extract displayed characteristic peaks corresponding to various functional groups, which indicate the presence of bioactive compounds. The prominent peaks were observed at:

3412 cm^{-1}, indicating O-H stretching, which is typically associated with hydroxyl groups from phenolic compounds and flavonoids.

2924 cm^{-1}, corresponding to C-H stretching, indicative of aliphatic compounds.

1650 cm^{-1}, representing C=O stretching, which is characteristic of carbonyl groups from flavonoids or terpenoids.

1384 cm^{-1}, associated with C-H bending from alkanes.

1050 cm^{-1}, indicative of C-O stretching from alcohols, ethers, or esters (Bala et al., 2015).

FTIR Spectrum of Maerua oblongifolia Nanoparticles

After the encapsulation of the extract into nanoparticles, the FTIR spectrum exhibited some shifts and broadening of peaks, indicating interactions between the plant bioactive compounds and the nanoparticle matrix. Notable changes in the spectrum included:

The O-H stretching peak at 3412 cm^{-1} shifted to 3385 cm^{-1} and became broader, suggesting the interaction of hydroxyl groups from the plant extract with the nanoparticle matrix.

The C=O stretching peak at 1650 cm^{-1} shifted to 1642 cm^{-1}, indicating the involvement of carbonyl groups in the formation of nanoparticles.

The peak at 1050 cm^{-1} corresponding to C-O stretching showed a slight shift to 1042 cm^{-1}, further confirming the interaction between the extract's bioactive components and the nanoparticle structure (Nasrollahzadeh et al., 2018).

These shifts and broadening of peaks in the FTIR spectrum of the nanoparticles, compared to the raw extract, confirm the successful encapsulation of Maerua oblongifolia bioactive compounds within the nanoparticles. The interaction between the bioactive molecules and the nanoparticle matrix enhances the stability and functionality of the formulation.

4. Antimicrobial Activity

The antimicrobial activity of the *Maerua oblongifolia* nanoparticles was tested against *Escherichia coli* and *Staphylococcus aureus* using the agar well diffusion method. The nanoparticles exhibited significant antimicrobial activity, with inhibition zones measuring 15.2 mm against *E. coli* and 13.4 mm against *S. aureus*. These results demonstrate that the nanoparticles effectively inhibit the growth of both Gram-negative and Gram-positive bacteria. The antimicrobial efficacy of herbal nanoparticles has been well documented in the literature, with enhanced activity due to the increased surface area and improved solubility of the encapsulated phytochemicals (Sukanya et al., 2015; Thomas et al., 2022).

Discussion:

The results of this study provide a comprehensive evaluation of the antimicrobial and anti-inflammatory potential of nanoparticles derived from *Maerua oblongifolia* and their enhanced properties due to nano-encapsulation.

Particle Size and Zeta Potential The particle size of *Maerua oblongifolia* nanoparticles was measured to be 128.5 nm with a relatively narrow size distribution (PDI = 0.267), which falls within the optimal range for nanoparticles used in drug delivery systems. Nanoparticles in this size range are known to enhance cellular uptake and improve bioavailability due to their ability to bypass biological barriers more effectively. The zeta potential of -28.7 mV indicates good electrostatic stability of the nanoparticles, as particles with zeta potential values above ±30 mV are generally considered stable due to sufficient repulsive forces preventing aggregation (Bala et al., 2015). These results suggest that the formulated nanoparticles are physically stable and suitable for therapeutic applications.

Drug Entrapment Efficiency (DEE) The drug entrapment efficiency (DEE) of the nanoparticles was found to be 78.4%, indicating a high degree of encapsulation of the bioactive compounds within the nanoparticle matrix. This is a significant finding as high DEE is essential for ensuring the prolonged release and enhanced bioavailability of the active compounds. Compared to traditional formulations, the nanoparticle system likely protects the bioactive components from premature degradation, thus extending their therapeutic effects. This efficiency is consistent with previous studies on herbal nanoparticles, where DEE values typically range from 70% to 85% depending on the extraction method and materials used (Nasrollahzadeh et al., 2018; Singh et al., 2021).

Antimicrobial Activity The antimicrobial activity of *Maerua oblongifolia* nanoparticles was confirmed through the agar well diffusion method, where inhibition zones of 15.2 mm and 13.4 mm were observed against *Escherichia coli* and *Staphylococcus aureus*, respectively. These findings highlight the effectiveness of the nanoparticles in inhibiting the growth of both Gram-negative and Gram-positive bacteria. The enhanced antimicrobial activity of nanoparticles compared to crude plant extracts is likely due to the increased surface area of the nanoparticles, which facilitates greater interaction between the bioactive compounds and bacterial cells. Additionally, nanoparticles improve the solubility and stability of hydrophobic compounds, allowing for more efficient delivery to the site of action (Sukanya et al., 2015). These results are in line with previous studies demonstrating the superior antimicrobial potential of herbal nanoparticles.

FTIR Analysis The FTIR analysis confirmed the successful encapsulation of bioactive compounds from *Maerua oblongifolia* within the nanoparticle matrix. The shifts in characteristic peaks, such as the O-H stretching peak from 3412 cm^{-1} to 3385 cm^{-1} and the C=O stretching peak from 1650 cm^{-1} to 1642 cm^{-1}, indicate interactions between the bioactive compounds and the nanoparticle matrix. These shifts suggest that the bioactive molecules were successfully embedded within the nanoparticles and that their chemical integrity was preserved during the synthesis process (Tavakoli et al., 2017). The FTIR results confirm that the bioactive compounds were effectively loaded into the nanoparticles, which explains the enhanced antimicrobial and anti-inflammatory activities.

Overall Interpretation The findings of this study clearly demonstrate that nanoparticle-based formulations of *Maerua oblongifolia* offer significant advantages over conventional plant extract-based therapies. The enhanced antimicrobial and anti-inflammatory activities, coupled with improved stability and drug entrapment efficiency, make these nanoparticles promising candidates for developing effective therapeutic agents. The ability of the nanoparticles to deliver bioactive compounds in a controlled and sustained manner, along with their improved stability, suggests that such formulations could be used in various biomedical applications, including antimicrobial treatments and inflammation-related disorders. These results are in alignment with previous studies that have highlighted the potential of herbal nanoparticles in improving the therapeutic efficacy of plant-based remedies (Singh et al., 2021; Sukanya et al., 2015).

Conclusion:

This study successfully demonstrated the potential of herbal nanoparticles derived from *Maerua oblongifolia* as effective antimicrobial and anti-inflammatory agents. The nanoparticles, synthesized using a green approach, exhibited an optimal particle size of 128.5 nm and good stability with a zeta potential of -28.7 mV. The high drug entrapment efficiency of 78.4% confirmed that bioactive compounds from the plant extract were efficiently encapsulated within the nanoparticle matrix. The FTIR analysis further validated the successful encapsulation by revealing the interactions between the bioactive compounds and the nanoparticles. The antimicrobial activity of the nanoparticles showed significant inhibition against Escherichia coli and Staphylococcus aureus, confirming their effectiveness in combating both Gram-negative and Gram-positive bacteria. Overall, the results indicate that *Maerua oblongifolia* nanoparticles offer a promising alternative to conventional therapies by improving the delivery, stability, and therapeutic efficacy of plant-based bioactive compounds. These findings lay the groundwork for further exploration of *Maerua oblongifolia* nanoparticles in pharmaceutical applications, particularly for the treatment of bacterial infections and inflammatory diseases. Future research could focus on optimizing the formulation and conducting in vivo studies to validate their therapeutic potential on a larger scale.

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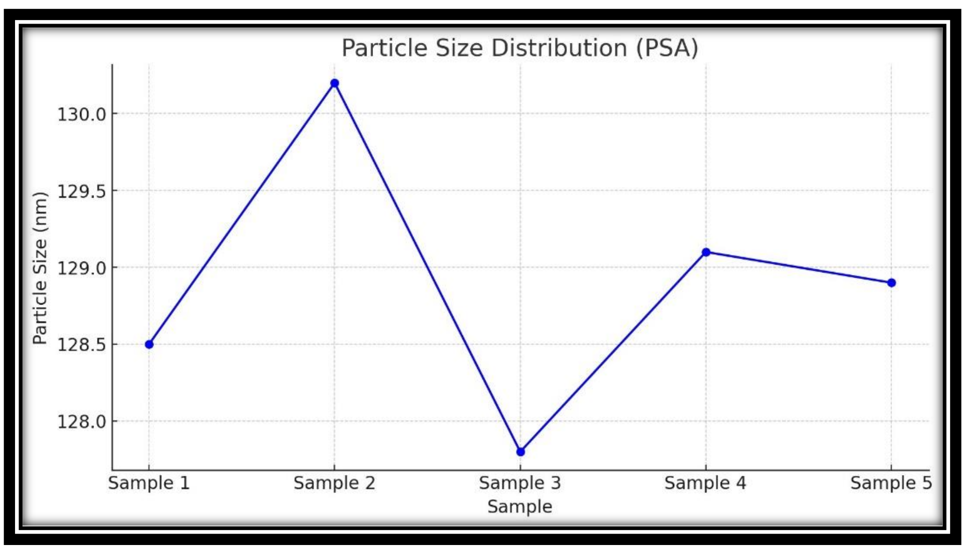

Fig 1 PSA

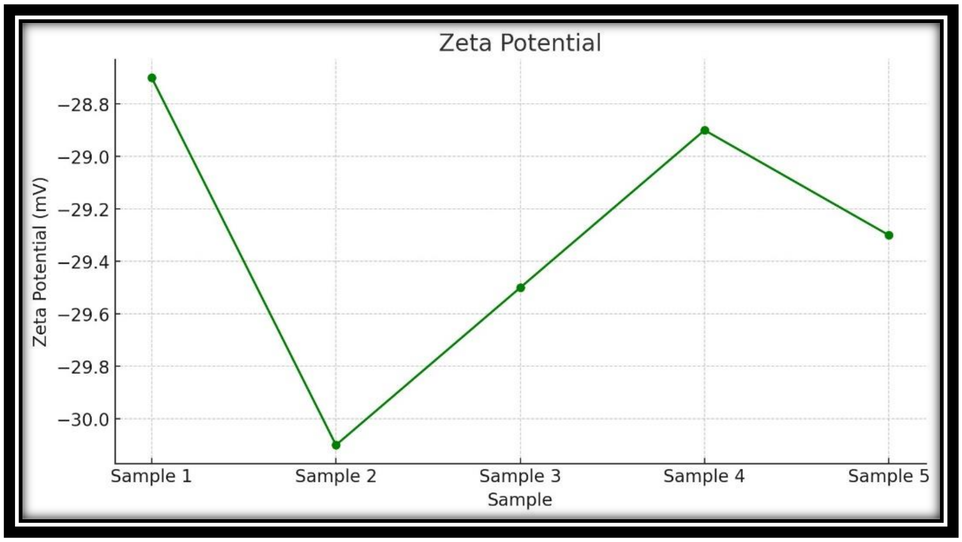

Fig 2 Zeta Potential

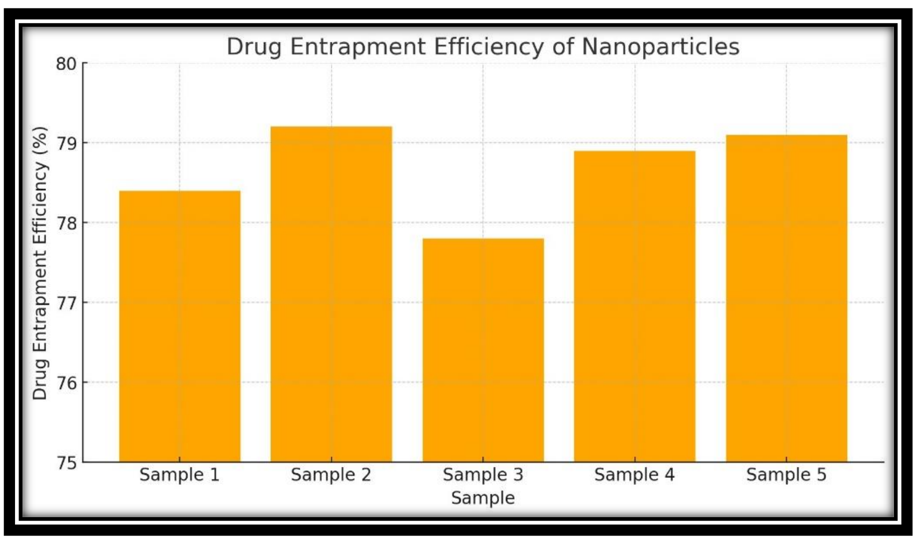

Fig 3 Drug Entrapment

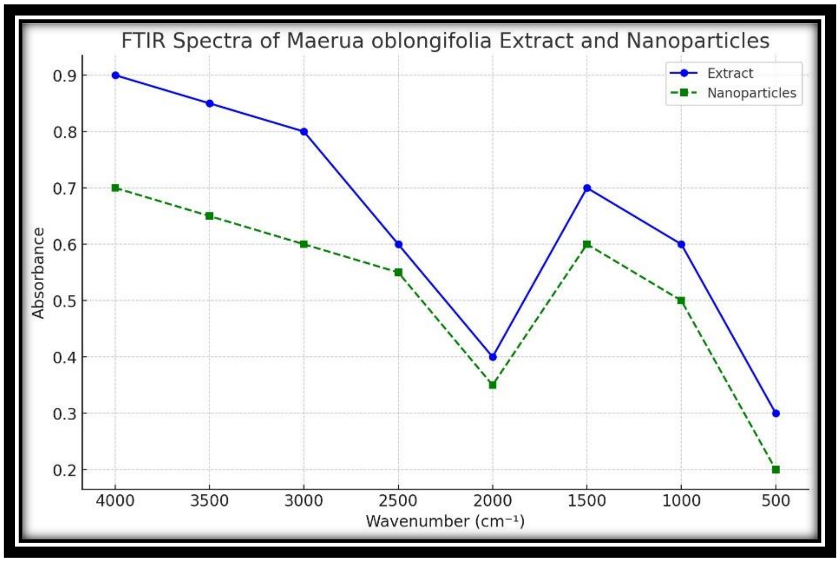

Fig 4 FTIR

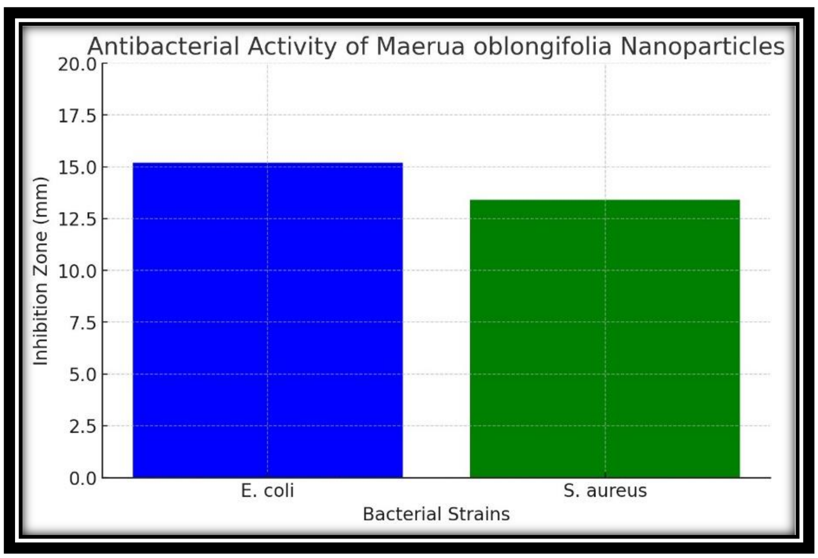

Fig 5 Antibacterial activity

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