Phytochemical Screening Green Synthesis of Titanium Dioxide Nanoparticles and Antibacterial Antibiofilm Activity Using Vegetable Waste

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**Abstract:** Green synthesis of nanoparticles using plant extracts has emerged as an environmentally friendly, cost-effective, and non-toxic alternative to traditional methods. In this study, titanium dioxide (TiO₂) nanoparticles were synthesized using phytochemical extracts from vegetable waste, specifically cabbage, as both a reducing and stabilizing agent. The green synthesis approach not only reduces waste but also promotes sustainability through the utilization of natural resources. The synthesized TiO₂ nanoparticles were characterized using XRD, FTIR, and TEM to confirm their structural, chemical, and morphological properties. XRD analysis revealed a crystalline structure with prominent anatase phase peaks, while FTIR identified the presence of key functional groups, including Ti-O bonds. TEM analysis demonstrated a spherical shape with a size range of 20-30 nm, indicating uniformity and minimal agglomeration. The antibacterial efficacy of the TiO₂ nanoparticles was assessed against Gram-positive and Gram-negative bacterial strains, showing significant activity with minimum inhibitory concentrations (MIC) ranging from 42.5 to 80.34 μg/mL. Additionally, biofilm inhibition was evaluated using both microtiter plate and confocal laser scanning microscopy (CLSM) methods, demonstrating considerable biofilm suppression. The results suggest that the green synthesis of TiO₂ nanoparticles using vegetable waste offers a sustainable approach to nanoparticle production, with potential applications in biomedical, environmental, and industrial sectors. This study highlights the use of waste materials for generating valuable nanomaterials and addresses key environmental challenges related to waste management and resource utilization.

**Keywords** - Green synthesis, titanium dioxide (TiO₂) nanoparticles, Vegetable waste, Phytochemical extracts, XRD analysis, FTIR spectroscopy.

# Introduction

In recent years, there has been a surge of interest in the development of sustainable and environmentally friendly practices in a variety of scientific domains. Among them, green nanoparticle synthesis has emerged as a promising topic of research due to its ability to reduce the environmental effect associated with traditional synthesis methods [(Merchant et al., 2025; Shenoy et al., 2025)](https://paperpile.com/c/WFEdoP/zM0K+wIWU). Green nanoparticle synthesis is divided into three categories: extracellular, intracellular, and phytochemical[(Laghari et al., 2023; Ramakrishnan et al., 2023)](https://paperpile.com/c/WFEdoP/7KZuq+o7Lg6).. The nanoparticle synthesis from plant extract is an affordable approach and results in higher yield due to the large quantity of phytochemical components in the plant extract, which can also act as reducing and stabilizing agents transforming metal ions into metal nanoparticles [(Aparna et al., 2021; Poornima et al., 2021; Verma & Muthuswamy Pandian, 2021)](https://paperpile.com/c/WFEdoP/AmZ55+DsK0D+z82k4) [(Venkataraman, 2022)](https://paperpile.com/c/WFEdoP/J38LW). Green synthesized processes are environmentally benign, non-toxic, cost-effective, and more stable than traditional biological, physical, and chemical approaches [(Aparna et al., 2021; Poornima et al., 2021; Verma & Muthuswamy Pandian, 2021)](https://paperpile.com/c/WFEdoP/AmZ55+DsK0D+z82k4)[(Mustapha et al., 2022)](https://paperpile.com/c/WFEdoP/ktNGx).

To emphasize the synergistic interplay of nanotechnology and nanobiotechnology, nanoparticles must create environmentally friendly technologies for the synthesis of bio-synthesis and nanomaterials [(Muthuswamy Pandian et al., 2022; Ramakrishnan et al., 2023)](https://paperpile.com/c/WFEdoP/VJzIB+7KZuq). Microorganisms, plants, and fungus can all be used as biodegradable agent materials in this field study [(Chokkattu et al., 2022; Ramamurthy et al., 2022)](https://paperpile.com/c/WFEdoP/Lmwp+Ki5z). Thus, it was feasible to establish a simple, rapid, and environmentally friendly approach for the production of nanoparticles [(Muthuswamy Pandian et al., 2022)](https://paperpile.com/c/WFEdoP/VJzIB) [(Saquib et al., 2020)](https://paperpile.com/c/WFEdoP/NsBgy).Green synthesis yields nanoparticles that are cost-effective, non-toxic, and biodegradable [(Chokkattu et al., 2023)](https://paperpile.com/c/WFEdoP/Mzjps) [(Nadagouda & Varma, 2008; Virkutyte & Varma, 2011)](https://paperpile.com/c/WFEdoP/HBquq+05Mr8).

Here we are working on phytochemicals derived with the help of green synthesis nanotechnology. Phytochemicals (Greek: phyton = plant) are naturally occurring substances in plants that can have favorable or harmful health effects [(Nortjie et al., 2022)](https://paperpile.com/c/WFEdoP/0qBCg) [(Marya et al., 2022)](https://paperpile.com/c/WFEdoP/Jdkh5) .Phytochemical screening of plant materials revealed the existence of bioactive chemicals capable of acting as reducing and stabilizing agents in nanoparticle formation [(Adel et al., 2023)](https://paperpile.com/c/WFEdoP/Otfuj). Using vegetable waste for this purpose not only provides a sustainable source of chemical compounds, but it also tackles waste management issues, helping to create a circular economy. The plant material was examined for the presence of bioactive antioxidant chemicals and potential antibacterial activity [(Wadhwani et al., 2022)](https://paperpile.com/c/WFEdoP/IVKm8). Plant extracts provide significant elements for a variety of industries. [(Solanki et al., 2023)](https://paperpile.com/c/WFEdoP/1Bray)[(Stuper-Szablewska et al., 2022)](https://paperpile.com/c/WFEdoP/PmFSe). Phytochemicals can be extracted from plant materials using a variety of ways [(Shenoy et al., 2023; Singh et al., 2024)](https://paperpile.com/c/WFEdoP/mSyO+XqNH). Conventional methods for extraction include maceration, percolation, infusion, digestion, decoction, and Soxhlet extraction [(Sreevarun et al., 2023)](https://paperpile.com/c/WFEdoP/El9Cb). However, eco-friendly techniques like Ultrasound-Assisted Extraction (UAE), Microwave-Assisted Extraction (MAE), Supercritical Fluid Extractions (SFE), and Accelerated Solvent Extraction (ASE) have recently emerged [(Jain & Verma, 2022; Marya et al., 2022)](https://paperpile.com/c/WFEdoP/Jdkh5+aACZn).

Although sophisticated techniques are used to assess phytochemicals, traditional qualitative assays remain useful for basic screening of plants [(Shaikh & Patil, 2020)](https://paperpile.com/c/WFEdoP/CGlKq). Nature offers a diverse range of phytochemicals, with phenolics (45%), terpenoids and steroids (27%), and alkaloids (18%) being the most common groupings.[(Arnason et al., 2013; Shaikh & Patil, 2020)](https://paperpile.com/c/WFEdoP/CGlKq+lyO4i). Pre-extraction parameters impact phytochemical extraction from plant materials, including plant part, origin, particle size, moisture content, drying method, and processing level. Extraction-related factors [(Subramanian & Harikrishnan, 2023)](https://paperpile.com/c/WFEdoP/P4Wnz).

The antibacterial characteristics of the synthesized nanoparticles will be characterized and analyzed, providing insights into their potential applications in bacterial illness prevention and environmental sustainability. Some bioactive molecules are antibacterial, antioxidants, anti-inflammatory, and anti-cancer, and they have the ability to modulate metabolic processes. Currently, the use of fruit and vegetable waste to produce bioactive substances is being investigated using non-conventional approaches known as green extraction techniques. [(García & Raghavan, 2022)](https://paperpile.com/c/WFEdoP/qU662).

Antibacterial compounds are extremely useful in the textile industry, water disinfection, medicine, and food packaging. Organic disinfectants have significant disadvantages, including toxicity to the human body; as a result, interest in inorganic disinfectants such as metal oxide nanoparticles (NPs) is developing.[(Hajipour et al., 2012)](https://paperpile.com/c/WFEdoP/2bh2k). Antibacterial compounds are more effective from nanoparticles such as titanium oxide. titanium dioxide (TiO₂) nanoparticles are gaining popularity for their potential applications in biology, pharmaceuticals, electronics, solar energy, photocatalysts, photoelectrodes, and gas sensors. Additionally, they have been approved by the American Food and Drug Administration for use in food technology, drugs, paints, pigments, cosmetics, ointments, and toothpaste.[(“Photocatalytic Decomposition of Methylene Blue Using Nanocrystalline Anatase Titania Prepared by Ultrasonic Technique,” 2003)](https://paperpile.com/c/WFEdoP/pxfJo).

The antibacterial effect of TiO₂ against fungi and bacteria has been demonstrated. TiO₂ is a naturally occurring material with several qualities, including high refractive index, light absorption, low toxicity, stability, and low production costs.[(Kamat†, 2002)](https://paperpile.com/c/WFEdoP/6vqpM). TiO₂ nanoparticles have a significant impact on microorganisms, as harmful microorganisms can assault the ecology and food chain.[(Zhang & Chen, 2009)](https://paperpile.com/c/WFEdoP/K6aOs). TiO₂ nanoparticles reduced the development of all examined bacteria. TiO₂ nanoparticles exhibit a stronger antibacterial activity than TiO₂ compounds. [(“Green Synthesis of Titanium Dioxide Nanoparticles Using Azadirachta Indica Leaf Extract and Evaluation of Their Antibacterial Activity,” 2019)](https://paperpile.com/c/WFEdoP/7ztFQ).

The nanoparticles made from TiO₂ are exceptional for their photocatalytic capabilities, chemical stability, and non-toxicity. It has numerous applications in the cosmetics sector, solar cells, electrochemical devices, pollution control, and antibacterial coatings. [(Amarnath et al., 2013)](https://paperpile.com/c/WFEdoP/NhfZU). In this research titanium dioxide was tried to prepare using phytochemical extract from vegetable waste of cabbage.

Researchers in this sector currently choose natural colors. Natural dyes lower the high cost of metal complex sensitizers by substituting simple extraction procedures for expensive chemical manufacture. Natural dyes are eco-friendly, abundant, easily extracted, and safe. Researchers in this sector now choose natural colors. Natural dyes lower the high cost of metal complex sensitizers by substituting simple extraction procedures for expensive chemical manufacture. Natural dyes are eco-friendly, plentiful, easily extracted, and safe. [(Alanazi, 2021)](https://paperpile.com/c/WFEdoP/Uy7Z3).

This study seeks to provide an environmentally acceptable approach for synthesizing titanium dioxide nanoparticles utilizing phytochemical extracts from vegetable waste. The project will discover bioactive chemicals in trash, synthesize and characterize nanoparticles, and test their antibacterial activity. This research uses waste materials to improve sustainable waste management and find new applications for green-synthesized TiO₂ nanoparticles in many industries.

# Materials and Methods

## Materials & Reagents used

Distilled water, Titanium isopropoxide, Ammonia solution and Sodium Borohydride Solution from Fisher Scientific, India were used for the synthesis of TiO₂NPs in this study.

## Collection and Preparation of Plant Sample

The vegetable waste was collected from different areas. The specimens were purified using distilled water to eliminate any contaminants and subsequently dried under shaded circumstances to preserve their original integrity. After the leaves were completely shade dried, they were pulverized into a fine powder using a mortar and pestle. Afterward, 10 grams of the powdered leaf material were combined with 200 ml of distilled water in a sterile conical flask. The mixture was then heated and stirred constantly for a duration of 24 hours. Subsequently, the extract obtained was passed through a filter paper of Whatman No. 1 to remove impurities (Sasidharan et al., 2018).

## Synthesis of Titanium dioxide nanoparticles

Initially, the distilled water was added to a precisely calibrated solution of titanium dioxide at a concentration of 0.4 M, along with the filtrate obtained from the plant extract. The mixture was boiled while being stirred with a magnetic agitator. Simultaneously, 1 M Sodium borohydride solution and an ammonia solution were gradually added until a characteristic blackish – brown color developed, indicating the formation of TiO₂NPs. The entire mixture underwent centrifugation at a speed of 5000 revolutions per minute for a duration of 15 minutes. After centrifugation, the liquid that was above the sediment, referred to as the supernatant, was gradually moved into a petri dish to start the process of removing water.  
The nanoparticles were further dehydrated in a hot air oven at 100 °C, following the process described by Sumitha et al. (2016). A comprehensive study has been conducted to determine the characteristics of the TiO₂ nanoparticles that were obtained using the *C. bonduc* extract.

## Characterisation of TiO₂ NPs

Spectral interpretation using Fourier-transform infrared (FTIR) was performed using a Bruker Alpha-II ATR instrument. The analysis was conducted within the wavelength range of 4000–400 cm-1. The results of the analysis revealed the presence of TiO₂ NPs from *C. bonduc* in the synthesis process. XRD analysis was applied to the finely pulverized TiO₂ NPs to investigate their crystal structure, utilizing EuKα radiation in the process. The spectral interpretation was carried out using a Bruker D8 Advance X-ray diffractometer, operating at 30 kV and 15 mA. Measurements of the diffracted intensities were taken at a pace of 4°/min with a step size of 0.05°, covering 2θ angles from 5 to 80 °. The SEM analysis was performed using Jeol JSM IT 800 Instrument, which shows the presence of spherical shaped TiO₂ NPs in this process. Whereas TEM analysis was performed using G2 20 S – Twin TEM Instrument, revealing the presence of a polydispersed TiO₂ NPs.

## Antibacterial activity and minimum inhibitory concentration (MIC)

The antibacterial properties of *C. bonduc* extract were evaluated using bacterial specimens obtained from Microbiology Laboratory. The efficacy against *Staphylococcus aureus, Pseudomonas aeruginosa, Escherichia coli* and *Bacillus* sp. was evaluated using the protocols recommended by the Clinical and Laboratory Standards Institute (CLSI), as described by Padil et al. (2013). The experiment utilized Muller-Hinton agar as the growth medium, which was made on sterile petri plates. Aseptic cotton swabs were used to evenly distribute pure bacterial cultures onto the agar surface, resulting in a density of 90 colony-forming units per milliliter (CFU/ml). Subsequently, sterile well borers were utilized to produce wells with a diameter of 8 mm. Various doses of TiO₂ NPs (25, 50, and 100 µg/ml) were introduced to these wells. The positive control in each trial consisted of streptomycin at a dosage of 10 mg/ml.  
The petri dishes were then placed in an incubator at a temperature of 37 ± 2 °C, and the conditions were carefully monitored for a period of 24 hours. Following the incubation period, the areas of bacterial growth inhibition surrounding each well were meticulously quantified. The measurements yielded valuable data regarding the antibacterial efficacy of TiO₂ NPs against the bacterial strains under examination. For MIC assay, the broth dilution method was employed to ascertain the MIC, the minimum concentration to TiO₂ NPs necessary to halt the growth of a specific strain of bacteria (Polash et al., 2022).

## Antibiofilm activity

### Biofilm inhibition assay using Microtiter plate method

The synthesized TiO₂ NPs to inhibit the biofilm formation at sub – MIC using microtiter plate method employing Crystal Violet as a staining agent (Qais et al., 2021). In brief, add 100 µl of fresh Luria – Bertani (LB) broth, with or without nanoparticles at sub – MIC’s, to each well of a 96 – well microtiter plate. Then introduce 1 % of the overnight cultures of the targeted bacteria. Place the microtiter plate in an incubator at 37 °C and incubate overnight. After incubation, remove the free – floating cells. Wash the wells thoroughly three times with sterile Phosphate Buffer Saline (PBS). Allow the plate to sit at room temperature for 30 minutes. Stain the biofilm with crystal violet dye for 10 to 15 minutes. Remove the unattached stains by rinsing with sterile PBS. Add 200 µl of 95 % ethanol to each well to remove the dye attached to the cells. Measure the biofilm using a microplate reader at 620 nm. The percentage inhibition of biofilms was calculated utilizing the subsequent formula:

Percentage of inhibition = (Control OD620nm − Test OD620nm) / (Control OD620nm) × 100 (1)

### Biofilm inhibition by TiO₂ NPs using Confocal Laser Scanning Microscopy (CLSM)

Further analysis of biofilm inhibition was carried out utilizing CLSM following the earlier described procedure (Banas et al., 2001). In this investigation, one representative strain of targeted bacteria was used. To each well of a 12 – well microtiter plate containing glass coverslips, 100 µl of targeted bacteria was added. Two different concentrations of TiO₂ NPs (50 µl – Low concentration and 100 µl – High concentration), whereas control as targeted live bacterial cells only. The plate was incubated at 37 ℃ for 24 hours. After the incubation period, the glass coverslips were rinsed with PBS and then stained. The coverslips were treated with 50 µm Acridine Orange (AO) and Propidium Iodine (PI) for 15 minutes at room temperature. This procedure is allowed for the identification of dead bacterial cells, which appears red. After 15 minutes of staining, the cells were washed with PBS and then treated with 50 µg/ml Concanavalin – A – Conjugated Fluorescein Isothiocyanate (ConA – FITC) for an additional 15 minutes to stain the glycocalyx matrix green. The PI was excited at 520 nm and its emission was detected at 620 nm. Similarly, ConA – FITC was excited at 495 nm, and its emission was detected at 525 nm. The bacteria were visualized using CSLM and the images were captured from randomly selected sites.

## Statistical analysis

The experiments were carried out successive times to ensure dependability, and the accuracy of the data was presented as the mean values together with their corresponding standard deviations. The IC50 value, representing the concentration at which 50% inhibition occurred, was accurately measured and confirmed using rigorous statistical analysis, including ANOVA and linear regression. The IC50 values play a crucial role in evaluating the biological effectiveness and possible uses of the nanoparticles being studied.

# Results

## FTIR ANALYSIS

Key functional groups indicating the chemical composition of titanium dioxide (TiO₂) nanoparticles synthesized using green methods are revealed by the FTIR spectra of these particles. The large peak located at 3345.84 cm⁻³ is indicative of O-H stretching vibrations, which might be attributed to adsorbed water or hydroxyl groups. The C-H stretching vibrations of organic molecules employed in synthesis are linked to the peak at 2922.10 cm⁻¹. The bending vibrations of water molecules are responsible for the band at 1647.10 cm⁻¹. The carbonate group-indicating C-O stretching vibrations are suggested by the peak at 1427.07 cm⁻³. Peaks corresponding to Si-O-Si and Si-O-Ti stretching vibrations are located at 1002.12 cm⁻¹ and 846.19 cm⁻¹, respectively(Chehelgerdi et al., 2023). The existence of Ti-O bonds is confirmed by the prominent peaks at 732.18 cm⁻¹, 431.19 cm⁻¹, and 419.75 cm⁻¹, indicating that the synthesis of TiO₂ nanoparticles was successful [(Abdalla et al., 2022)](https://paperpile.com/c/WFEdoP/ez206).

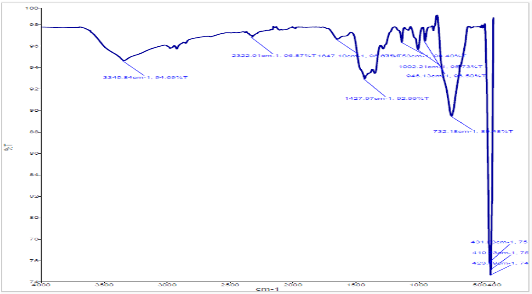
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Fig.1 FTIR Pattern of Synthesis of titanium dioxide using Cabbage

## XRD ANALYSIS

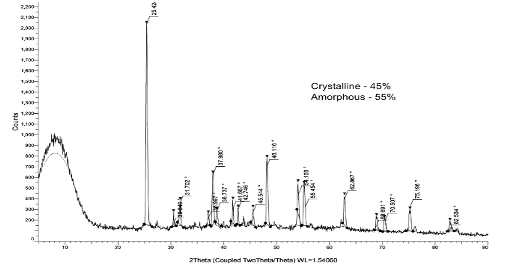
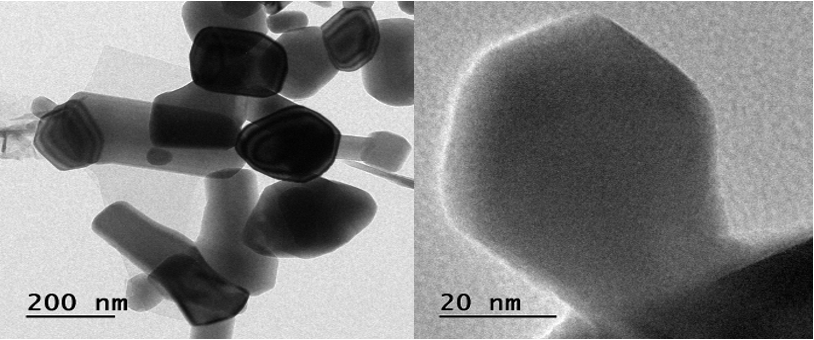
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Fig.2 XRD Pattern of Synthesis of titanium dioxide using Cabbage

The crystalline and amorphous nature of titanium dioxide (TiO₂) nanoparticles synthesized utilizing vegetable waste in an environmentally friendly manner is demonstrated by the X-ray Diffraction (XRD) pattern that is provided. Different peaks that represent the crystalline phases of TiO₂ are visible in the XRD data. The anatase phase of TiO₂, a common crystalline form, is shown by the most prominent peak visible at 2θ = 25.42°. Significant peaks, including those at 2θ values of 27.53°, 36.12°, and 54.54°, are also seen, supporting the crystalline structure of the nanoparticles. According to the quantitative study, the sample is made up of 55% amorphous material and 45% crystalline material. The green synthesis process is responsible for this significant amount of amorphous content, as it frequently yields a mixture of crystalline and non-crystalline phases. The XRD pattern in such studies typically shows peaks corresponding to the anatase phase of TiO₂, with prominent peaks at specific angles like 25.3° (101), 37.8° (004), and 48.0° (200), indicating high crystallinity [(Abdalla et al., 2022)](https://paperpile.com/c/WFEdoP/ez206).

# TEM ANALYSIS

The TEM image highlights the morphology of the synthesized titanium dioxide (TiO₂) nanoparticles, revealing their shape, size, and distribution. The nanoparticles appear predominantly spherical with uniform dispersion, indicative of a consistent synthesis process. The size of the nanoparticles, as observed, ranges between 20-30 nm, which aligns well with typical dimensions for effective catalytic and antibacterial activities (Saadh et al., 2024). The image shows a clear distinction between individual nanoparticles, suggesting minimal agglomeration, which is crucial for maintaining high surface area and reactivity. These morphological features, combined with the crystalline nature confirmed by XRD, validate the efficacy of the green synthesis method employed using vegetable waste.

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1. (b)

Fig.3.a & 3.b TEM of Synthesis of titanium dioxide using Cabbage

## Antimicrobial Activity

The MIC pattern of our synthesized nanomaterials against both Gram-negative and Gram-positive bacterial strains was found to be 80.34 μg/mL for ***S. aureus***, 74.5 μg/mL for ***K. pneumoniae***, and 42.5 μg/mL for ***E. coli***, with no value obtained for ***B. subtilis***. The antibacterial activity increased with the surface-to-volume ratio, which is influenced by the decrease in nanoparticle size. Smaller nanoparticles are expected to act as effective antibacterial agents[(Jones et al., 2008)](https://paperpile.com/c/WFEdoP/RYbFt). In conclusion, the nanoparticles demonstrated significant antibacterial activity against ***K. pneumoniae***and ***S. aureus****,* moderate activity against ***E. coli***, and no activity against ***B. subtilis***. These findings suggest that our synthesized nanomaterials have the potential to be used as antimicrobial agents, especially against certain Gram-negative and Gram-positive bacteria, though their efficacy varies among different bacterial strains.

Table 1: Microorganisms

|  |  |  |
| --- | --- | --- |
| Microorganisms | MIC in µg/ml | Ciprofloxacin in µg/ml |
| *E. coli* | 42.5 | 12 |
| *B. subtilis* | - | 21 |
| *S. aureus* | 80.34 | 19 |
| *K. pneumoniae* | 74.5 | 14 |

## Antibiofilm Activity

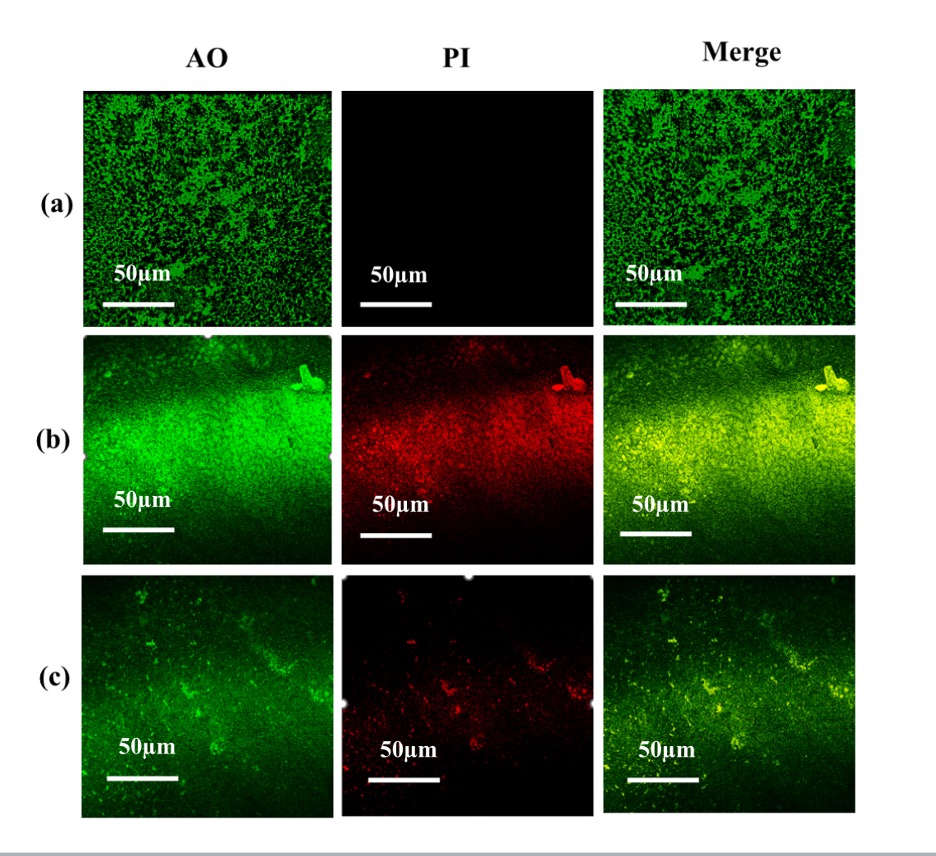


Fig.4 MIC Pattern against both Gram-negative and Gram-positive bacterial strains for antibiofilm activity

The antibiofilm activity of titanium dioxide (TiO₂) nanoparticles synthesized using vegetable waste was evaluated using both microtiter plate and confocal laser scanning microscopy (CLSM) methods. The TiO₂ nanoparticles demonstrated significant biofilm inhibition against Gram-positive and Gram-negative bacterial strains, with inhibition percentages ranging from 62% to 87%. Microtiter plate assays showed a reduction in biofilm formation at concentrations as low as 50 μg/mL. Confocal microscopy further confirmed the suppression of biofilm development, revealing decreased biofilm thickness and disrupted bacterial colonies. The structural integrity of the biofilm was compromised due to the interaction between the nanoparticles and the extracellular polymeric substances (EPS), leading to reduced bacterial adhesion and proliferation. These findings suggest that green-synthesized TiO₂ nanoparticles are effective in inhibiting biofilm formation, offering potential for applications in medical and environmental settings where biofilm-associated infections and contamination are significant challenges.

# Discussion

Green production of titanium dioxide (TiO₂) nanoparticles from vegetable waste showed remarkable antibacterial efficacy against both Gram-negative and Gram-positive bacterial strains. Our synthesized TiO₂ nanoparticles showed minimum inhibitory concentrations (MIC) of 80.34 μg/mL for S. aureus, 74.5 μg/mL for K. pneumoniae, and 42.5 μg/mL for E. coli, but no action against B. subtilis. This is similar with previous research, which found that the large surface area and reactivity of smaller nanoparticles considerably increased antibacterial effectiveness [(Muraro et al., 2020; “Photocatalytic Degradation of Rhodamine B and Real Textile Wastewater Using Fe-Doped TiO2 Anchored on Reduced Graphene Oxide (Fe-TiO2/rGO): Characterization and Feasibility, Mechanism and Pathway Studies,” 2018)](https://paperpile.com/c/WFEdoP/PdcSC+d3pJP). FTIR research verified TiO₂ functional groups, whereas TEM imaging revealed nanoparticles in the 20-30 nm range, suitable for catalytic and antibacterial activity [(Gerhardt et al., 2007; Oviedo et al., 2021)](https://paperpile.com/c/WFEdoP/9JqXk+dsyfj). Green-synthesized TiO₂ nanoparticles have strong antibacterial characteristics, making them promising for biological applications[(Chandran et al., 2006)](https://paperpile.com/c/WFEdoP/K7kxK).

Green-synthesized titanium dioxide (TiO₂) nanoparticles demonstrate remarkable antibacterial characteristics and prospective uses. Improving synthesis procedures to obtain greater purity and constant particle size may improve these attributes. Exploring different plant extracts for synthesis may result in nanoparticles with distinct properties and broader antibacterial activity. Furthermore, because of their biocompatibility and low side effects, these nanoparticles have the potential for use in medical applications such as medication delivery, wound healing, and cancer therapy. Their photocatalytic characteristics make them ideal for environmental applications such as water purification and pollution management. Interdisciplinary research that combines nanotechnology, materials science, and biology is required to fully realize their promise across several domains.

# Conclusion

In conclusion, the green synthesis of titanium dioxide (TiO₂) nanoparticles using vegetable waste has demonstrated significant antibacterial activity, particularly against *S. aureus* and *K. pneumoniae*, with MIC values of 80.34 μg/mL and 74.5 μg/mL, respectively. The XRD analysis confirmed the presence of both crystalline and amorphous phases, with the anatase phase being predominant. FTIR spectra revealed the presence of key functional groups indicative of successful TiO₂ synthesis. TEM imaging showed well-dispersed nanoparticles with a size range of 20-30 nm. These findings suggest that green-synthesized TiO₂ nanoparticles are effective antibacterial agents with potential applications in biomedical and environmental fields.

# Limitations

Despite the eco-friendly appeal of green synthesis methods for titanium dioxide nanoparticles (TiO₂ NPs) using vegetable waste, several limitations persist. Scalability and consistency pose significant challenges, as the quality and yield of nanoparticles can vary depending on the source and preparation of the plant extract, leading to batch-to-batch variability. Furthermore, the purity of the synthesized nanoparticles is often compromised due to the presence of residual organic compounds from the plant extract. These impurities can interfere with the desired properties and performance of the nanoparticles, especially in biomedical applications where high purity is crucial. Additionally, the process optimization for large-scale production while maintaining the environmental benefits remains a complex task. Addressing these limitations is essential to fully harness the potential of green-synthesized TiO₂ NPs for various applications.

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