

# Synthesis, and Morphological Characterization of TiO<sub>2</sub>-Based Nano-Composite for Antimicrobial Applications

Muayad Raheem Hussein<sup>1</sup>, Sabah Hasan Jumaah<sup>2,\*</sup>, Ali N. Majeed<sup>3</sup>

\* boshraqs@yahoo.com

<sup>1</sup> University of sumer, college of science, physics department, Thi-Qar, Iraq

<sup>2</sup> Mustansiriyah university, college of science, physics department, Baghdad, Iraq

<sup>3</sup> Scientific Research Commission, Baghdad, Iraq

Received: August 2025

Revised: November 2025

Accepted: December 2025

DOI: 10.22068/ijmse.4261

**Abstract:** In the current study, titanium dioxide (TiO<sub>2</sub>) nanoparticles were synthesised and subsequently combined with chitosan (CS) and silver (Ag) to enhance their antimicrobial activity. The synthesised TiO<sub>2</sub>, TiO<sub>2</sub>-CS, and TiO<sub>2</sub>-CS-Ag nanocomposites were characterised using various techniques to thoroughly assess their structural, morphological, and compositional properties. XRD analysis substantiated the phase transition from anatase to rutile upon incorporation of chitosan and silver, accompanied by a reduction in nanoparticle dimensions. FTIR spectra corroborated the presence of functional groups associated with chitosan and silver, while FESEM revealed morphological modifications, notably the emergence of polygonal nanostructures within the TiO<sub>2</sub>-CS-Ag composite. The antibacterial efficacy of the synthesized nanocomposites was evaluated against *Escherichia coli* (*E.coli*) and *Staphylococcus aureus* (*S.aureus*). Although pure TiO<sub>2</sub> showed minimal antibacterial activity, the TiO<sub>2</sub>-CS and TiO<sub>2</sub>-CS-Ag composites exhibited substantial inhibition zones, with the TiO<sub>2</sub>-CS-Ag composite showing the greatest efficacy, attributable to the synergistic interaction between chitosan and silver nanoparticles. BET analysis revealed that the augmented antimicrobial activity was associated with the increased surface area of the TiO<sub>2</sub>-CS-Ag nanocomposite.

**Keywords:** TiO<sub>2</sub> nanocomposite, Chitosan, Silver nanoparticles, Antibacterial activity, Green synthesis, Morphological characterization.

## 1. INTRODUCTION

Nanotechnology has enabled the development of advanced materials with superior physicochemical properties applicable across diverse biomedical and environmental fields. Among these innovative materials, titanium dioxide (TiO<sub>2</sub>)-based nanocomposites have emerged as a focal point of research due to their remarkable photocatalytic, antibacterial, and biocompatible attributes [1, 2]. TiO<sub>2</sub> nanoparticles have found extensive application in antimicrobial coatings, water purification processes, and biomedical devices, primarily owing to their capability to produce reactive oxygen species (ROS) upon light exposure, which effectively eradicates microbial pathogens [3, 4]. Nonetheless, unmodified TiO<sub>2</sub> nanoparticles are constrained by several limitations, including insufficient surface area, the recombination of electron-hole pairs, and restricted activity under visible light irradiation [5]. To address these limitations, composite formulations integrating biopolymers and metallic nanoparticles have been investigated to bolster antimicrobial effectiveness and stability [6].

Chitosan (CS), a naturally occurring biopolymer

sourced from chitin, has been the subject of extensive scholarly investigation due to its biocompatibility, biodegradability, and inherent antimicrobial properties. The functionalization of chitosan with TiO<sub>2</sub> nanoparticles engenders synergistic antimicrobial effects by facilitating the disruption of bacterial cell membranes while augmenting ROS generation [7, 8]. Furthermore, silver (Ag) nanoparticles are recognised for their broad-spectrum antimicrobial activities, which are attributed to their ability to interact with bacterial cell walls, generate ROS, and interfere with cellular metabolic processes [9, 10]. The integration of Ag nanoparticles into TiO<sub>2</sub>-CS nanocomposites is hypothesised to enhance antimicrobial efficacy and sustain bioactivity [11, 12].

Several studies have demonstrated that modification of TiO<sub>2</sub> with biopolymers and metallic nanoparticles not only enhances its surface characteristics but also facilitates the controlled release of antimicrobial agents while augmenting its biocidal efficacy against both Gram-positive and Gram-negative bacteria [13, 14]. In this regard, Hoang et al. fabricated polyvinyl alcohol (PVA)/CS/TiO<sub>2</sub>@Ag nanofiber using the electrospinning technique in

order to examine its antibacterial activity against *Escherichia coli* (*E.coli*) and *Staphylococcus aureus* (*S.aureus*) bacteria. The results showed that the resultant nanofiber shows appropriate antibacterial activity against both bacteria [15]. In another study, a fish gelatin/CS/TiO<sub>2</sub>-Ag composite showing high antibacterial activity was prepared. Because of its antibacterial activity, the composite was expected to be a suitable candidate for the food packaging industry [16].

Owing to the abovementioned properties, the current study endeavours to prepare TiO<sub>2</sub>-CS and TiO<sub>2</sub>-CS-Ag nanocomposites and characterize their morphology and structure by means of X-ray diffraction (XRD), Fourier-transform infrared spectroscopy (FTIR), field-emission scanning electron microscopy (FESEM), energy-dispersive X-ray spectroscopy (EDXS), Brunauer-Emmett-Teller (BET), and Barrett-Joyner-Halenda (BJH). Moreover, the antibacterial activity of the synthesised nanocomposites will be rigorously evaluated against *E.coli* and *S.aureus* bacteria to ascertain their antimicrobial efficacy.

## 2. EXPERIMENTAL PROCEDURES

### 2.1. Preparation of TiO<sub>2</sub> Nanoparticles

TiO<sub>2</sub> nanoparticles were synthesized utilizing the hydrothermal technique. Initially, a precursor solution was formulated by combining 5 mL of ethanol with 5 mL of acetic acid under magnetic agitation for 15 min. Subsequently, 5 mL of titanium tetraisopropoxide (TTIP) was added dropwise, followed by continuous stirring for an additional 15 min to facilitate the hydrolysis of the precursor. To initiate the hydrolysis reaction, 100 mL of deionised water was rapidly added, followed by 2 mL of concentrated nitric acid. The resultant solution was heated under reflux at 80°C for 1 hour, during which a colour transition from white to pale blue was observed.

For the hydrothermal treatment, the solution was transferred into a 100 mL stainless steel autoclave equipped with a Teflon liner to ensure chemical inertness. The autoclave was hermetically sealed and heated to 200°C for 10 hours to facilitate the formation of nanoparticles under meticulously controlled temperature and pressure conditions. Upon completion, the mixture was centrifuged at 10,000 rpm for 5 min to isolate the solid phase, which was then washed 3 times with ethanol. The resulting precipitate was dried at 60°C in an oven

and subsequently ground into a fine powder for further characterization.

### 2.2. Preparation of TiO<sub>2</sub>-CS Nanocomposite

A chitosan solution was formulated by solubilising 0.5 g of chitosan powder in 50 mL of deionised water, augmented with 0.5 mL of acetic acid, at 80°C for 30 min. In a separate procedure, 0.5 g of TiO<sub>2</sub> nanoparticles was uniformly dispersed in 50 mL of deionized water while being agitated for 30 min. Subsequently, the two resultant solutions were combined and heated at 70°C for 15 min to obtain a homogeneous mixture.

### 2.3. Preparation of TiO<sub>2</sub>-CS-Ag Nanocomposite

In order to fabricate TiO<sub>2</sub>-CS-Ag nanocomposite, in addition to the preparation of two solutions in section 2.2, a separate silver precursor solution was formulated by dissolving 0.1 g of silver nitrate in 10 mL of deionised water under continuous agitation at ambient temperature. The three resultant solutions were combined and heated at 70°C for 15 min to ensure a uniform mixture.

### 2.4. Implant Coating Procedure

Titanium skull mesh implants were coated using the dip-coating technique with a dip-coating device from Iranian Toos Nano. The implants were systematically immersed in the prepared TiO<sub>2</sub>, TiO<sub>2</sub>-CS, and TiO<sub>2</sub>-CS-Ag solutions at a meticulously controlled immersion rate of 10 mm/min. Each cycle comprised a 10-second immersion followed by a 5-min drying interval, and this process was reiterated for a total of 50 cycles. After the coating procedure, the samples were dried in an oven at 120 °C for 24 hours to ensure complete adhesion of the coating layers.

## 3. RESULTS AND DISCUSSION

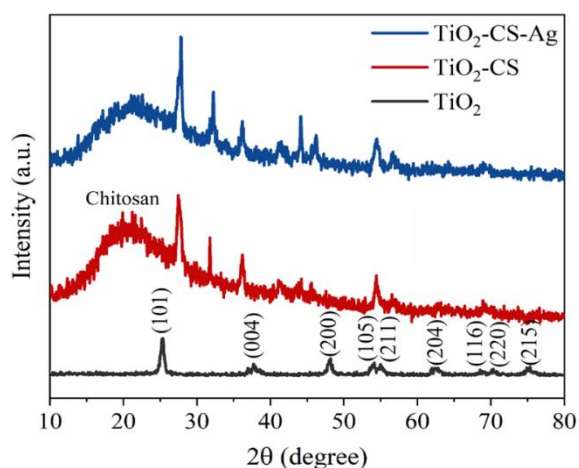
### 3.1. Characterization Analyses

Figure 1 demonstrates the XRD patterns of TiO<sub>2</sub>, TiO<sub>2</sub>-CS, and TiO<sub>2</sub>-CS-Ag recorded in the 2θ range from 10 to 80 degrees. Based on the X-ray diffractogram of TiO<sub>2</sub> nanoparticles, several diffraction peaks are observed at the 2θ of 25.3, 37.7, 48.2, 54.1, 55.0, 62.3, 68.5, 70.3, and 75.3 degrees. In accordance with the JCPDS file No. 21-1272, the aforementioned peaks are respectively assigned to Miller indices of (101), (004), (200), (105), (211), (204), (116), (220), and (215), corresponding to anatase phase of TiO<sub>2</sub> [1-3]. No other peaks are observed except those related to

TiO<sub>2</sub> nanoparticles, indicating that our fabricated sample is free of impurities and has high purity. The average dimension of TiO<sub>2</sub> nanoparticles was calculated by means of Equation 1, which is known as Debye–Scherrer’s formula [4]:

$$D = \frac{K\lambda}{\beta \cos\theta} \quad (1)$$

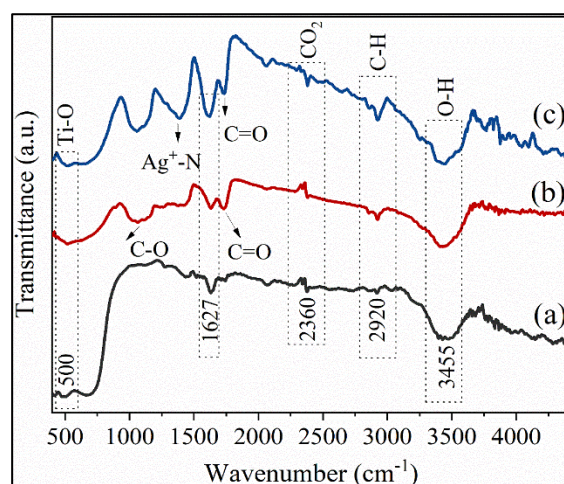
Where D stands for the mean size of the particles, K signifies the Scherrer constant with the value of 0.98,  $\lambda$  represents the X-ray wavelength equal to 1.541 Å, and  $\beta$  denotes the full width at half maximum (FWHM). By taking the sharpest peak at 25.3 degrees into account for the calculation of the mean size of TiO<sub>2</sub> nanoparticles, a value of 10.92 nm was obtained for this sample.



**Fig. 1.** XRD patterns of TiO<sub>2</sub>, TiO<sub>2</sub>-CS, and TiO<sub>2</sub>-CS-Ag in the 2 $\theta$  range from 10 to 80 degrees

Compositing TiO<sub>2</sub> nanoparticles with chitosan has resulted in some changes in their XRD pattern (Figure 1). Accordingly, a broad peak has appeared at approximately 20 degrees, attributed to amorphous chitosan [5, 6]. Moreover, some of the diffraction peaks relevant to TiO<sub>2</sub> nanoparticles are observed. Using Equation 1, an average particle size of 3.43 nm was obtained for TiO<sub>2</sub>-CS, indicating that the compositing process can reduce nanoparticle size. The inclusion of Ag particles in the TiO<sub>2</sub>-CS nanocomposite has had a negligible effect on its XRD pattern (Figure 1). Accordingly, the broad peak at 20°, relevant to amorphous chitosan, and the diffraction peaks of TiO<sub>2</sub> nanoparticles are visible. No peak pertinent to Ag particles can be seen, which may be as a result of high dispersion of Ag particles within the nanocomposite or overlapping the XRD peaks of Ag with TiO<sub>2</sub> [17, 18]. Among all the fabricated samples, the smallest size was achieved for TiO<sub>2</sub>-CS-Ag

nanocomposite (3.01 nm); therefore, this sample could benefit from a high surface-to-volume ratio. FTIR spectroscopy was another characterisation technique used to probe the functional groups in the prepared samples. According to Figure 2a exhibiting the FTIR spectrum of TiO<sub>2</sub> nanoparticles, a broad peak can be observed at the wavenumber of 3455 cm<sup>-1</sup>, which arises from the hydroxyl (O-H) groups related to water molecules [7, 8]. The peak at 2920 cm<sup>-1</sup> is pertinent to the stretching vibration of C-H [6]. The peak at 2360 cm<sup>-1</sup> corresponds to physisorbed carbon dioxide (CO<sub>2</sub>) molecules present in air onto the sample [13]. In addition to peaking at ~3455 cm<sup>-1</sup>, the one centered at 1627 cm<sup>-1</sup> is correlated to water molecules [12]. The characteristic peaks relevant to the Ti-O tensile and Ti-O-Ti bridging modes typically appear in the wavenumber varying from 400 to 1000 cm<sup>-1</sup> [11]; hence, the absorption band at 500 cm<sup>-1</sup> is ascribed to TiO<sub>2</sub>. For the TiO<sub>2</sub>-CS nanocomposite (Figure 2b), the peaks at 1731 and 1064 cm<sup>-1</sup> respectively relevant to the absorption bands of C=O and C-O, originate from chitosan [6]. Moreover, the absorption band corresponding to TiO<sub>2</sub> nanoparticles in the nanocomposite is observed at 500 cm<sup>-1</sup>. Figure 2c illustrates the FTIR spectrum of TiO<sub>2</sub>-CS-Ag nanocomposite. Accordingly, all the absorption bands interpreted for its counterpart without Ag (Figure 2b) can be seen. In addition to those peaks, a well-defined peak is observed at about 1388 cm<sup>-1</sup>, which is attributed to Ag<sup>+</sup>-N coordination bonds [9].



**Fig. 2.** FTIR spectra of a) TiO<sub>2</sub>, b) TiO<sub>2</sub>-CS, and c) TiO<sub>2</sub>-CS-Ag

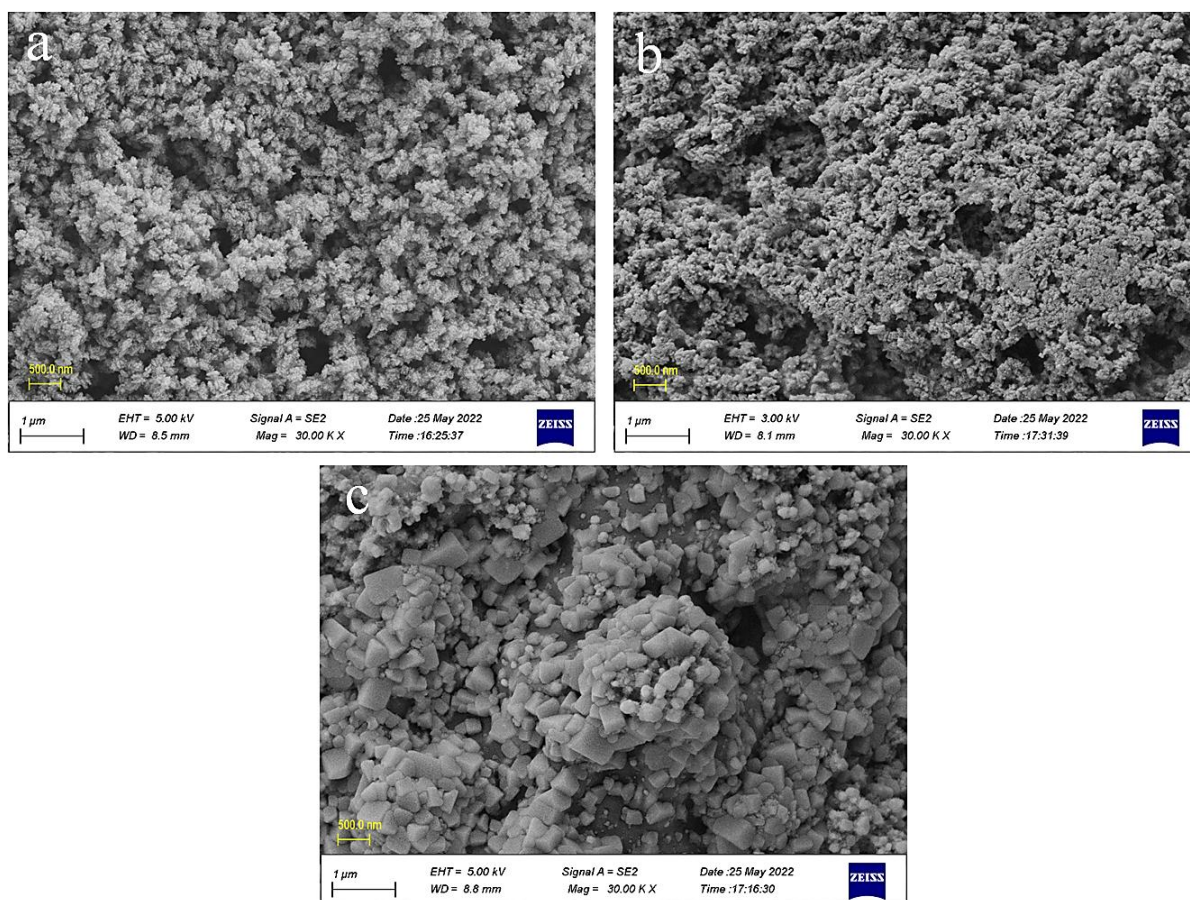
Figure 3 represents FESEM images of the prepared samples. According to Figure 3a, the FESEM image of TiO<sub>2</sub> shows spherical-shaped nanoparticles.

The size of the clusters composed of TiO<sub>2</sub> nanoparticles changes from 58 nm to 344.9 nm. Compositing TiO<sub>2</sub> nanoparticles with chitosan has caused a negligible effect on their morphology. The clusters of spherical-shaped TiO<sub>2</sub> nanoparticles are also found for the TiO<sub>2</sub>-CS nanocomposite (Figure 3b), whose size varies from 40.65 nm to 120.9 nm. Comparing the morphology of TiO<sub>2</sub> and TiO<sub>2</sub>-CS (see Figures 3a and 3b) demonstrates that the compositing process could cause more agglomeration among clusters. Without chitosan, the TiO<sub>2</sub> nanoparticles are more evenly distributed. Introduction of Ag particles into the TiO<sub>2</sub>-CS nanocomposite matrix has significantly altered its morphology. Flower-like species consisting of polygonal nanoparticles are observed in the FESEM image of the TiO<sub>2</sub>-CS-Ag nanocomposite (Figure 3c). The size of the polygonal nanoparticles is 89.02-341.2 nm. As shown in Figure 4a, the EDXS pattern of TiO<sub>2</sub> nanoparticles shows a pronounced peak for oxygen (O) at about 0.5 keV. In addition, the characteristic peaks of the titanium (Ti) element

are easily found at approximately 0.5 and 4.5 keV. The peaks of oxygen and titanium elements originate from the TiO<sub>2</sub> nanoparticles. Like TiO<sub>2</sub>, the EDXS pattern of TiO<sub>2</sub>-CS nanocomposite reveals the peaks of oxygen and titanium elements relevant to TiO<sub>2</sub> nanoparticles (Figure 4b). Moreover, the carbon (C) peak can be detected at about 0.25 keV. The peaks of carbon and oxygen are associated with the presence of chitosan in the nanocomposite. For the TiO<sub>2</sub>-CS-Ag nanocomposite (Figure 4c), the peaks of oxygen and titanium, indicative of TiO<sub>2</sub> nanoparticles, and the peaks of carbon and oxygen, related to chitosan, are clearly distinguished. Additionally, the conspicuous peaks of the silver (Ag) element are discernible at about 3.0 and 3.75 keV.

### 3.2. Specific Surface Area Investigation

The specific surface areas of TiO<sub>2</sub>, TiO<sub>2</sub>-CS, and TiO<sub>2</sub>-CS-Ag were examined by BET analysis. Figure 5 demonstrates the nitrogen absorption-desorption isotherms for the prepared samples. Additionally, the BET results are listed in Table 1.



**Fig. 3.** The FESEM images of a) TiO<sub>2</sub>, b) TiO<sub>2</sub>-CS, and c) TiO<sub>2</sub>-CS-Ag at various magnifications

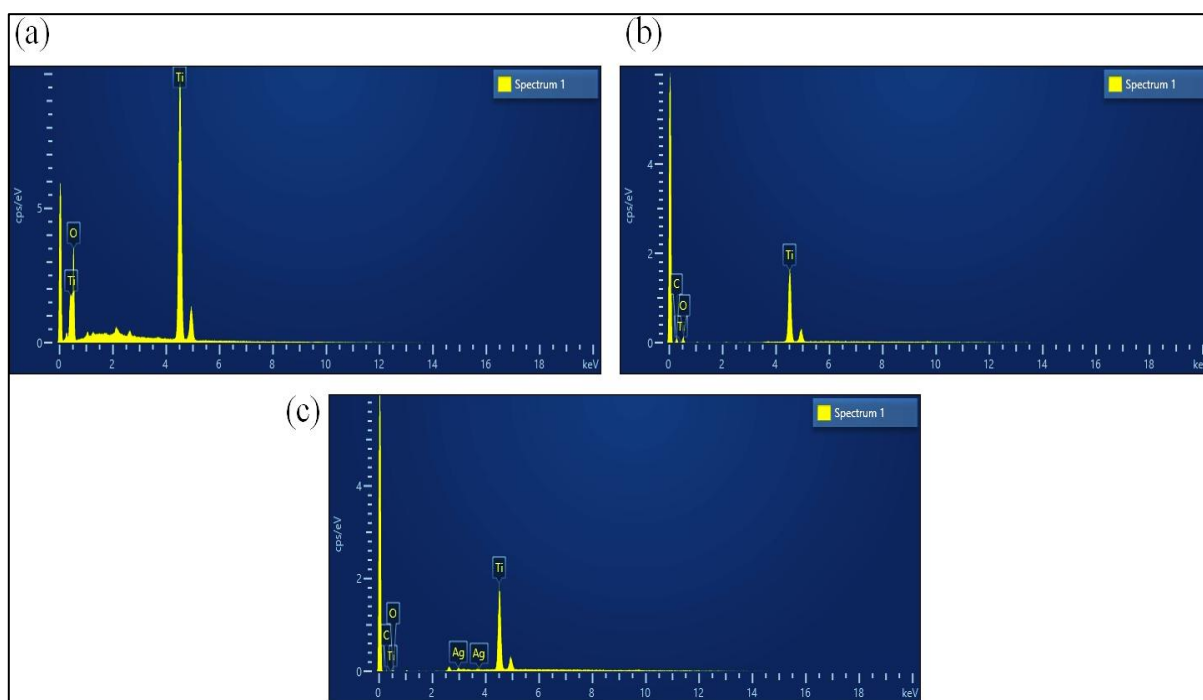


Fig. 4. The EDXS patterns of a) TiO<sub>2</sub>, b) TiO<sub>2</sub>-CS, and c) TiO<sub>2</sub>-CS-Ag

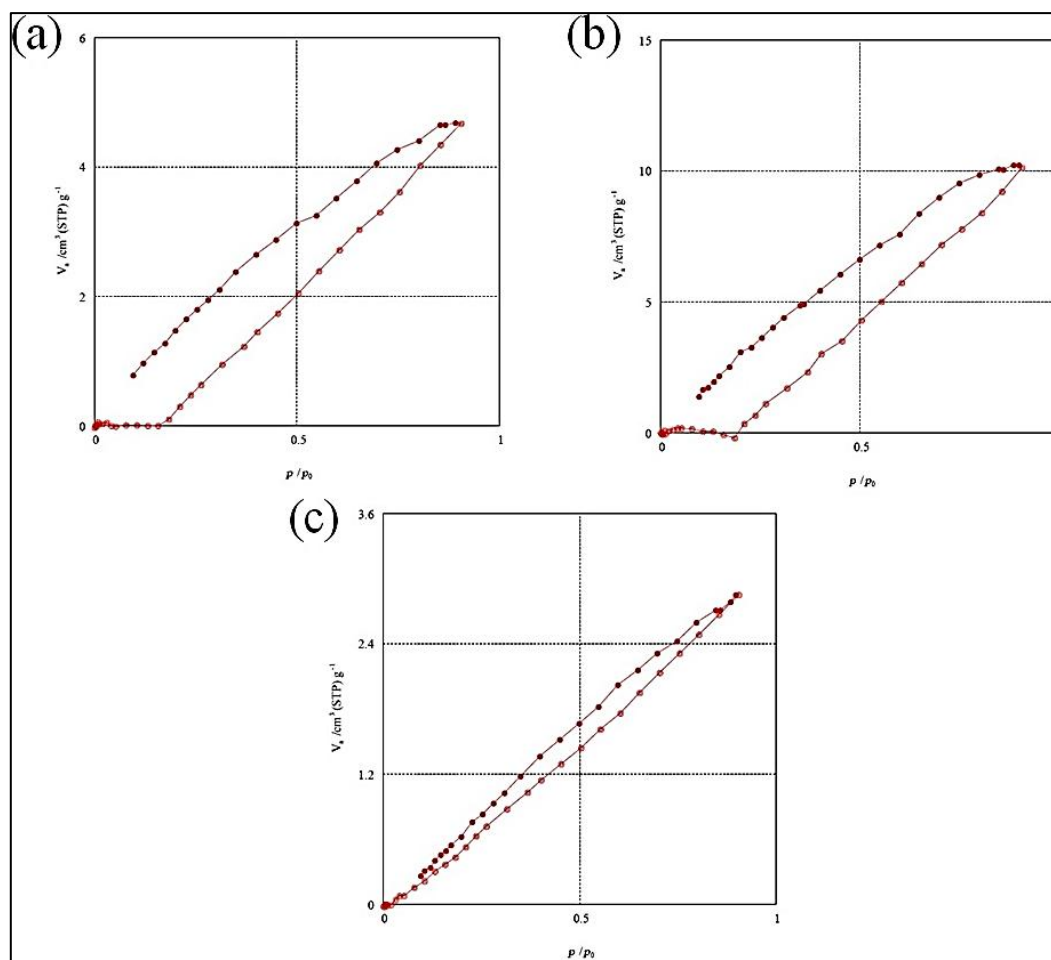


Fig. 5. Nitrogen adsorption-desorption isotherm of a) TiO<sub>2</sub>, b) TiO<sub>2</sub>-CS, and c) TiO<sub>2</sub>-CS-Ag

**Table 1.** Data obtained from the BET analysis conducted for TiO<sub>2</sub>, TiO<sub>2</sub>-CS, and TiO<sub>2</sub>-CS-Ag

Sample	Mean pore diameter (nm)	Effective pore volume (cm <sup>3</sup> /g)	Effective surface area (m <sup>2</sup> /g)
TiO <sub>2</sub>	2020.7	0.0072335	0.014319
TiO <sub>2</sub> -CS	85304	0.015655	0.00073408
TiO <sub>2</sub> -CS-Ag	106.48	0.0044144	0.16582

Accordingly, all the samples exhibit a mean pore diameter exceeding 50 nm, indicating they are macropores. The average pore diameter achieved for TiO<sub>2</sub> nanoparticles is 2020.7 nm. Compositing TiO<sub>2</sub> with chitosan has resulted in an increment in mean pore diameter. In this regard, the sample with chitosan shows an average pore diameter of 85304 nm, which is higher than that of the samples without chitosan (TiO<sub>2</sub> nanoparticles) and with chitosan and Ag (TiO<sub>2</sub>-CS-Ag nanocomposite). Introduction of Ag resulted in a significant decrease in mean pore diameter, and the sample containing both chitosan and Ag showed the lowest mean pore diameter. In terms of effective surface area, the highest value is obtained for TiO<sub>2</sub> nanoparticles composited with chitosan and included with Ag. This can be tied to the nanocomposite dimension, where the least amount was observed for TiO<sub>2</sub>-CS-Ag, as evidenced by XRD analysis. A smaller size provides more active surface area. Interestingly, the TiO<sub>2</sub>-CS nanocomposite had a lower effective surface area than its counterpart without chitosan. In addition to BET, BJH analysis was performed to determine the pore-size distribution. According to BJH absorption (Figure 6a) and desorption (Figure 6b) curves of TiO<sub>2</sub> nanoparticles, both mesopores (2–50 nm) and macropores (>50 nm) can be found. Compositing TiO<sub>2</sub> with chitosan had a negligible effect on pore size distribution. Like TiO<sub>2</sub>, the BJH absorption (Figure 6c) and desorption (Figure 6d) curves of TiO<sub>2</sub>-CS nanocomposite demonstrate a mixture of mesopores and macropores. Mixing TiO<sub>2</sub> nanoparticles with CS has increased pore volume. Introduction of Ag within TiO<sub>2</sub>-CS nanocomposite decreased the pore volume. The TiO<sub>2</sub>-CS-Ag nanocomposite also showed a combination of mesopores and macropores (Figures 6e, f).

### 3.3. Antibacterial Activity Measurements

Antibacterial activities of TiO<sub>2</sub>, TiO<sub>2</sub>-CS, and TiO<sub>2</sub>-CS-Ag against E.coli and S.aureus, respectively, as gram-negative and gram-positive bacteria, were examined by means of the disk diffusion method. This technique is typically performed by spreading

the microorganism on an agar culture medium and then placing the antibacterial agent as a spot on the medium. Antibacterial agents are expected to inhibit germination and prevent the growth of microorganisms. The circular area around the spot of the antibacterial agent, or, in other words, the zone of inhibition, is measured as a parameter for assessing the agent's effectiveness. A larger inhibition zone indicates greater susceptibility of the microorganism to the antibacterial agent.

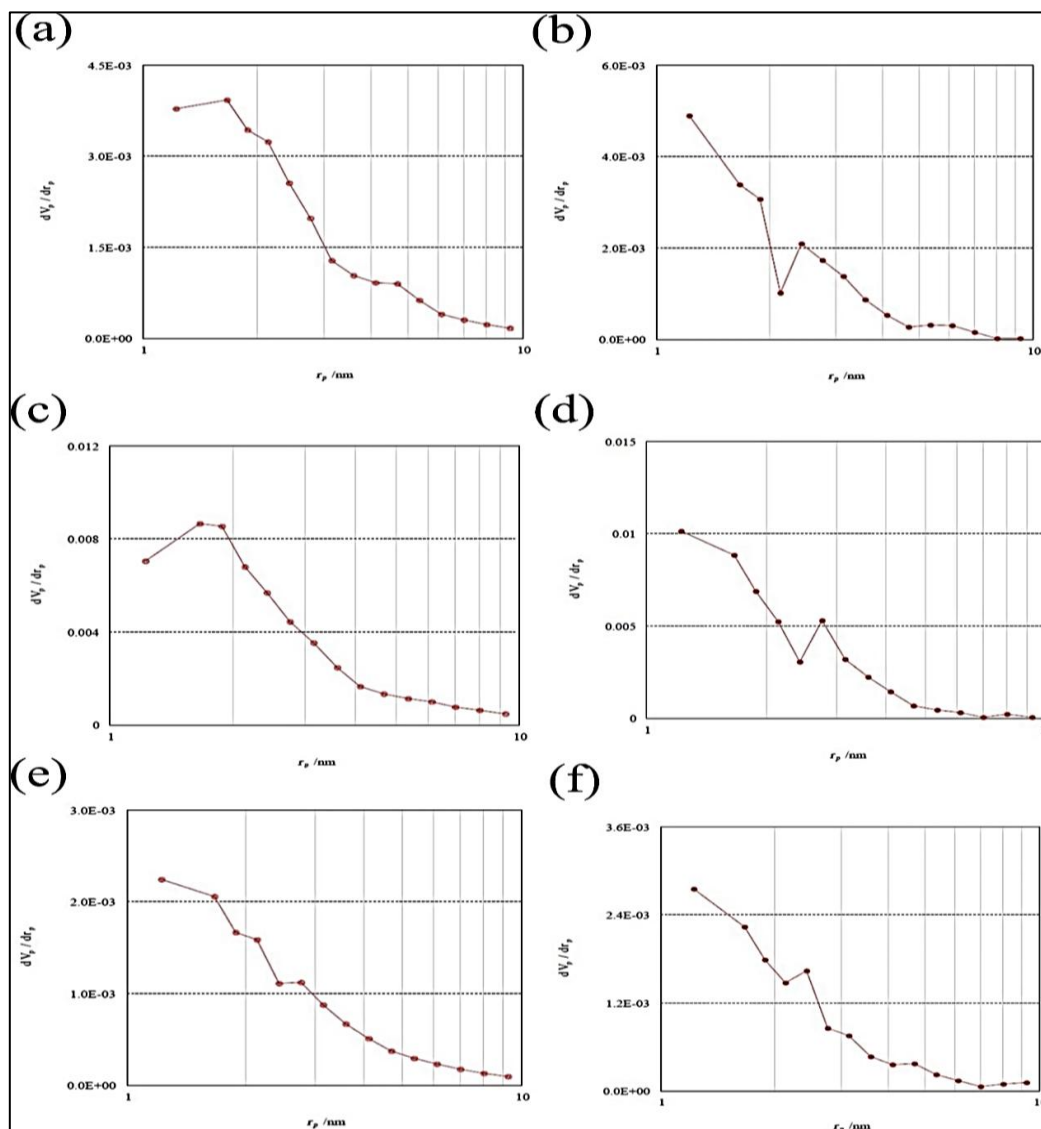
Figure 7 demonstrates the disk diffusion test carried out for TiO<sub>2</sub>, TiO<sub>2</sub>-CS and TiO<sub>2</sub>-CS-Ag against E.coli. Accordingly, the largest inhibition zone is observed after 24 hours for the TiO<sub>2</sub>-CS-Ag nanocomposite among all the samples. As a result, TiO<sub>2</sub>-CS-Ag exhibits high antibacterial activity against E. coli. No zone of inhibition can be detected for the blank sample, nor for TiO<sub>2</sub> nanoparticles. Therefore, they lack any antibacterial activity against E.coli. On the other hand, compositing TiO<sub>2</sub> nanoparticles with chitosan has resulted in a zone of inhibition smaller than that observed for the TiO<sub>2</sub>-CS-Ag nanocomposite. High antibacterial activity of TiO<sub>2</sub>-CS-Ag nanocomposite against E. coli can be related to two reasons, one of which is the presence of silver particles acting as powerful antibacterial agents against both gram-positive and gram-negative bacteria [10]. The other reason is the role of both chitosan and Ag in reducing the size of TiO<sub>2</sub> nanoparticles and subsequently, increasing their surface area, as evidenced by both XRD and BET analyses.

In addition to E.coli, the antibacterial activity of our prepared samples was investigated against S.aureus, a gram-positive bacterium. Figure 8 exhibits the zone of inhibition recorded for TiO<sub>2</sub>, TiO<sub>2</sub>-CS and TiO<sub>2</sub>-CS-Ag against S. aureus after 24 hours.

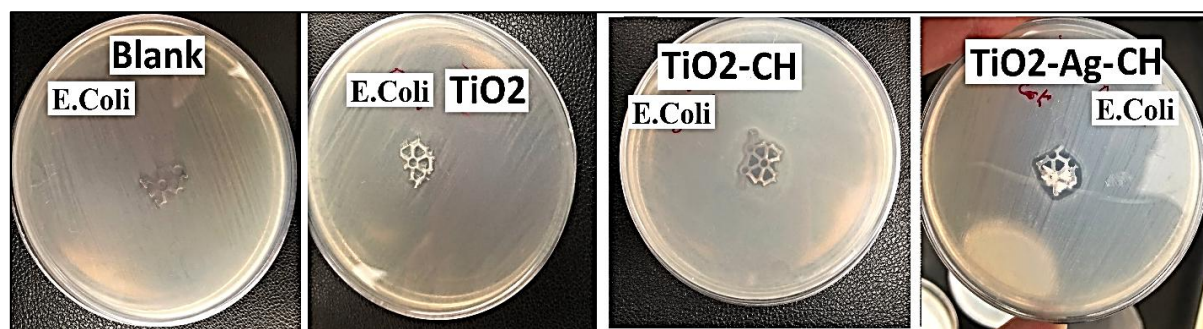
Accordingly, the largest inhibition zone is observed with the TiO<sub>2</sub>-CS-Ag nanocomposite, indicating that this sample could serve as an antibacterial agent against Gram-positive bacteria. Like the TiO<sub>2</sub>-CS-Ag nanocomposite, its Ag-free counterpart also shows antibacterial activity against S.aureus. On the other hand, no inhibition zone is observed

for TiO<sub>2</sub> nanoparticles; consequently, this sample exhibits no antibacterial activity against S.aureus. The results of antibacterial activity measurements

corroborate that the TiO<sub>2</sub>-CS-Ag nanocomposite could be an ideal antibacterial agent against both gram-negative and gram-positive bacteria.



**Fig. 6.** The BJH curves for a,b) TiO<sub>2</sub>, c,d) TiO<sub>2</sub>-CS, and e,f) TiO<sub>2</sub>-CS-Ag. For each sample, the first and second curves are the absorption and desorption curves, respectively



**Fig. 7.** Zone of inhibition obtained for the disks without case study samples and with TiO<sub>2</sub>, TiO<sub>2</sub>-CS and TiO<sub>2</sub>-CS-Ag against E.coli

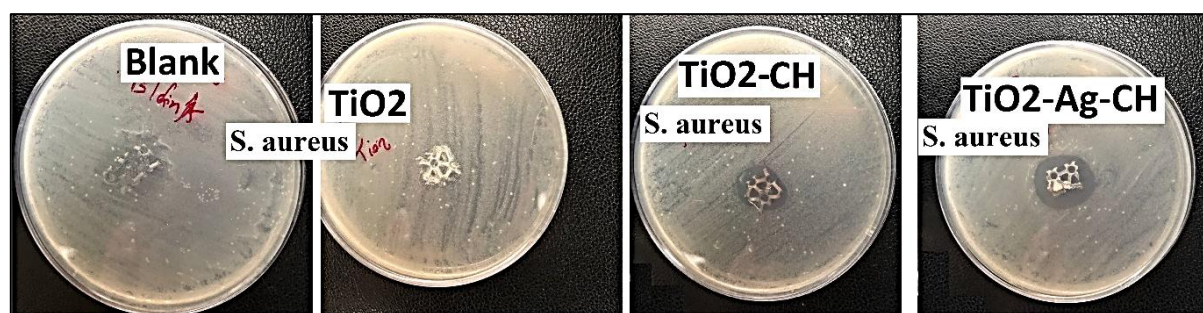


Fig. 8. Zone of inhibition recorded for the disks without case study samples and with TiO<sub>2</sub>, TiO<sub>2</sub>-CS and TiO<sub>2</sub>-CS-Ag against S.aureus

#### 4. CONCLUSIONS

In this work, TiO<sub>2</sub> nanoparticles and their nanocomposites, including TiO<sub>2</sub>-CS and TiO<sub>2</sub>-CS-Ag, were synthesised to evaluate their antibacterial activity. All the characterization tests were used to verify the synthesis of the samples. In accordance with XRD test, including solely chitosan or both chitosan and Ag into TiO<sub>2</sub> nanoparticles changed their X-ray diffractogram. In addition, the nanocomposites exhibited a smaller average size than the nanoparticles. FTIR spectroscopy confirmed the preparation of the samples, with characteristic peaks for TiO<sub>2</sub>, chitosan, and Ag observed. TiO<sub>2</sub> nanoparticles and their composite with chitosan showed almost identical morphologies. However, the inclusion of Ag into the TiO<sub>2</sub>-CS nanocomposite completely changed its morphology. Among all the samples, only TiO<sub>2</sub>-CS and TiO<sub>2</sub>-CS-Ag nanocomposites showed antibacterial activity against E.coli and S.aureus, with the highest effectiveness observed for the Ag-containing nanocomposite. The excellent antibacterial activity of TiO<sub>2</sub>-CS-Ag nanocomposites was attributed to the presence of Ag particles and their high surface area, as confirmed by BET analysis.

The results of our study put forward that TiO<sub>2</sub>-CS-Ag nanocomposites could be ideal for medical applications. They can be adapted to address health issues caused by E.coli and S.aureus.

#### REFERENCES

- [1] Nagaraj, G., et al., Facile synthesis of improved anatase TiO<sub>2</sub> nanoparticles for enhanced solar-light driven photocatalyst. *SN Applied Sciences*, 2020. 2: p. 1-9.
- [2] Jamil, S. and M. Fasehullah, Effect of temperature on structure, morphology, and optical properties of TiO<sub>2</sub> nanoparticles. *Mater Innov*, 2021. 1(01): p. 22-8.
- [3] Mallick, S., et al., PLA-TiO<sub>2</sub> nanocomposites: Thermal, morphological, structural, and humidity sensing properties. *Ceramics International*, 2018. 44(14): p. 16507-16513.
- [4] Tamarani, A., R. Zainul, and I. Dewata. Preparation and characterization of XRD nano Cu-TiO<sub>2</sub> using sol-gel method. in *Journal of Physics: Conference Series*. 2019. IOP Publishing.
- [5] Castillo, B.E., et al., Potential use of chitosan-TiO<sub>2</sub> nanocomposites for the electroanalytical detection of imidacloprid. *Polymers*, 2022. 14(9): p. 1686.
- [6] Taspika, M., et al., Influence of TiO<sub>2</sub>/Ag particles on the properties of chitosan film. *Advances in Natural Sciences: Nanoscience and Nanotechnology*, 2020. 11(1): p. 015017.
- [7] El-Desoky, M., et al., Synthesis, structural and electrical properties of PVA/TiO<sub>2</sub> nanocomposite films with different TiO<sub>2</sub> phases prepared by sol-gel technique. *Journal of Materials Science: Materials in Electronics*, 2020. 31(20): p. 17574-17584.
- [8] Deyab, M., A.A. Nada, and A. Hamdy, Comparative study on the corrosion and mechanical properties of nano-composite coatings incorporated with TiO<sub>2</sub> nanoparticles, TiO<sub>2</sub> nano-tubes, and ZnO nano-flowers. *Progress in Organic Coatings*, 2017. 105: p. 245-251.
- [9] Zhang, B., Y. Luo, and Q. Wang, Development of silver/ $\alpha$ -lactalbumin nanocomposites: a new approach to reduce silver toxicity. *International Journal of Antimicrobial Agents*, 2011. 38(6): p. 502-509.
- [10] Li, J., Xie, B., Xia, K., Li, Y., Han, J. and Zhao, C., Enhanced antibacterial activity of silver doped titanium dioxide-chitosan composites under visible light. *Materials*, 2018. 11(8): p.1403.

- [11] Dong, Z., Li, R. and Gong, Y., Antibacterial and freshness-preserving mechanisms of chitosan-nano-TiO<sub>2</sub>-nano-Ag composite materials. *Coatings*, 2021. 11(8): p.914.
- [12] Zafar, N., Uzair, B., Niazi, M.B.K., Samin, G., Bano, A., Jamil, N., Sajjad, S. and Mena, F., Synthesis and characterization of potent and safe ciprofloxacin-loaded Ag/TiO<sub>2</sub>/CS nanohybrid against mastitis causing E.coli. *Crystals*, 2021, 11: p. 319.
- [13] Abutalib, M.M. and Rajeh, A.J.P.T., Enhanced structural, electrical, mechanical properties and antibacterial activity of Cs/PEO doped mixed nanoparticles (Ag/TiO<sub>2</sub>) for food packaging applications. *Polymer Testing*, 2021. 93: p. 107013.
- [14] Usman Khan, M., Rehman, W., Bibi, S., Alanazi, M.M., Alanazi, A.S., Rasheed, L., Khan, S., Tariq Gillani, S.U. and Tauqeer, A., Synthesis, characterization, and antimicrobial and nematocidal activities of chitosan-based silver-doped titanium dioxide. *ACS omega*, 2023. 8: pp. 19341-19350.
- [15] Hoang, T.D., Nguyen, T.C., Doan, T.T., Ngo, T.D., Nguyen, T.Y., Ngo, B.T., Tran, T.T. and Le, T.L., Preparation and photocatalytic and antibacterial properties of polyvinyl alcohol/chitosan/TiO<sub>2</sub>@Ag electrospun nanofibers. *Thin Solid Films*, 2024. 797: p. 140344.
- [16] Lin, D., Yang, Y., Wang, J., Yan, W., Wu, Z., Chen, H., Zhang, Q., Wu, D., Qin, W. and Tu, Z., Preparation and characterization of TiO<sub>2</sub>-Ag loaded fish gelatin-chitosan antibacterial composite film for food packaging. *International Journal of Biological Macromolecules*, 2020. 154: pp. 123-133.
- [17] Rana, A., Parashar, S., Singh, D., Singh, K., Chanda, D., Pal, A., Srivastava, R. and Sharma, S.N., Exploring the dermal safety of green-synthesized Ag-TiO<sub>2</sub> nanocomposites for topical applications. *RSC advances*, 2025, 15(12): pp. 9320-9334.
- [18] Zhang, C., Hua, H., Liu, J., Han, X., Liu, Q., Wei, Z., Shao, C. and Hu, C., Enhanced photocatalytic activity of nanoparticle-aggregated Ag-AgX (X= Cl,Br)@TiO<sub>2</sub> microspheres under visible light. *Nano-Micro Letters*, 2017, 9(4): p. 49.