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PAPER

Preparation and characterization of graphene oxide quantum dots/silver nanoparticles and investigation of their antibacterial effects

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Abstract

Water, constituting 75% of Earth and vital for sustaining life, faces global contamination challenges, causing approximately 2 million annual deaths from waterborne diseases, as reported by the World Health Organization. Technological strides in water purification leverage antibacterial materials to combat this issue. At the forefront is silver nanoparticles (AgNP), renowned for antimicrobial efficacy. Their action involves damaging bacterial cells and hindering metabolism, causing structural and physiological alterations in microbial membranes. Graphene oxide (GO) emerges as a potent biocide, and when combined with AgNP, it enhances antibacterial activity. The resulting composite, known as antibacterial graphene oxide quantum dots (GOQD), exhibits photocatalytic behavior when exposed to sunlight or UV rays, generating reactive oxygen species (ROS). This synergistic composite, particularly the GOQD/AgNP combination, proves effective in eliminating bacteria and fungi from water. In a recent study, GOQD was synthesized, and the GOQD/AgNP combination was prepared. Structural analyses, utilizing techniques such as FTIR, Zeta sizer, and TEM, revealed heightened antibacterial activity with increasing AgNP ratios. The GOQD/AgNP samples formed inhibition zones of 11.75 mm, 10 mm, and 9.88 mm against pathogenic bacteria *Escherichia coli (E. coli)*, *Salmonella typhi (S. typhi)*, and *Staphylococcus aureus (S. aureus)*, respectively. Notably, the GOQD/AgNP composite demonstrated a synergistic antibacterial effect, showcasing its potential for widespread applications. This material holds promise for deployment in drinking water treatment plants and water storage tanks, ensuring water safety for consumption. Beyond water purification, the composite's antibacterial properties hint at significant potential in medical and industrial realms, marking a crucial step toward safeguarding water sources and enhancing global public health.

1. Introduction

Clean water is an indispensable resource for all life on Earth, with human survival, ecological balance, and economic stability heavily reliant on its availability. This vital substance constitutes a significant proportion of our planet, holding immense importance for human health, ecosystems, and the economy (Bruyninckx 2018). Access to clean water is a fundamental necessity, serving as a bulwark against waterborne diseases (Murphy *et al* 2014). In agriculture, clean water is imperative for cultivating crops and meeting the global food demand. Moreover, clean water forms the bedrock for industrial processes, energy production, and international trade. Regions blessed with abundant clean water resources tend to experience more favorable conditions for economic growth (Lee and He 2022). Water-based ecosystems, including rivers, lakes, wetlands, and seas, provide habitats for myriad species, underscoring the need for safeguarding clean water resources. Preserving these resources is paramount for ensuring a sustainable water supply for future generations. This entails stringent control of pollution sources, efficient management of industrial waste, adoption of responsible agricultural practices, and the implementation of effective wastewater treatment (Bielawski 2021).

One of the pressing challenges accompanying technological advancements is the contamination of water resources by fungi and bacteria at various stages of the water cycle (Murphy *et al* 2014). Alongside these

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developments, several pollutants contribute to water pollution, originating from wastewater discharged by sewage systems, industrial facilities, and agricultural activities. Rainwater, too, can transport surface pollutants into water bodies, facilitating the proliferation of harmful bacteria. Similarly, the leaching of pesticides and fertilizers into water sources renders the water susceptible to contamination (Pradhan *et al* 2022). Regrettably, these factors collectively result in approximately 2 million annual deaths due to waterborne diseases, as reported by the World Health Organization (Cissé 2019).

The utilization of antibacterial materials presents an efficacious approach to combat water resource contamination stemming from bacteria and fungi (Kordbacheh and Heidari 2023). Incorporating such materials into filtration systems and coatings holds the potential to enhance water safety and cleanliness. Antibacterial materials can be effectively employed in water filtration, where nanoscale-designed antibacterial coatings or filters serve as effective tools for trapping or eradicating bacteria and fungi Rautela *et al* (2021). These interventions play a pivotal role in purifying water. Furthermore, critical water infrastructure components such as storage tanks, pipes, and supply equipment can benefit from the protective qualities of antibacterial coatings, thereby inhibiting the growth of microorganisms on inner surfaces and ensuring the cleanliness of the water (Choudhury *et al* 2022).

Antibacterial materials also find application in water disinfection processes, with silver nanoparticles emerging as a promising candidate. By introducing silver nanoparticles into water, they efficiently exterminate bacteria and fungi, thereby rendering the water suitable for human consumption, particularly when integrated into water treatment facilities (Bhardwaj *et al* 2021). It is noteworthy that as materials approach the nanoscale, their properties undergo distinctive transformations. In this context, the proportion of atoms on the material's surface becomes increasingly significant (Asha and Narain 2020). Consequently, the surface-to-volume ratio of nanomaterials increases, giving rise to changes in their electronic, optical, magnetic, and mechanical properties (Koçak and Karasu 2018). Given that a considerable portion of biological molecules and structures exists at the nanoparticle scale, nanomaterials bear tremendous promise for biomedical research (Nienhaus *et al* 2020).

Silver nanoparticles have proven their mettle in diverse applications, including environmental protection, water remediation, monitoring, and agricultural wastewater treatment (Mustapha *et al* 2022, Palani *et al* 2023). These nanoparticles exhibit potent antimicrobial properties, rendering them broad-spectrum antimicrobial agents effective against a wide array of microbes encompassing bacteria, viruses, and fungi (Upadhyay *et al* 2019). Their efficacy can be attributed to unique characteristics such as their heightened surface area, intrinsic toxicity, and potential interactions with cellular components (Abdel Azeem *et al* 2021). Studies have revealed that silver nanoparticles induce structural and physiological changes in microbial cell membranes. These changes entail nanoparticle accumulation, alterations in membrane permeability and potential, as well as the inhibition of membrane-bound respiratory proteins. The release of silver ions (Ag+) from silver nanoparticles is a noteworthy phenomenon, with these ions adhering to the surfaces of bacterial and fungal cells (Xu *et al* 2021). Subsequent changes ensue, impacting membrane integrity and increasing permeability, thereby leading to cell content leakage and the ultimate demise of microbial cells. Of particular note is the disruption of the bacterial respiratory chain by silver nanoparticles, impeding vital physiological processes and culminating in cell death (Jahan *et al* 2023). Moreover, these nanoparticles are renowned for their capacity to generate reactive oxygen species, including hydroxyl and superoxide radicals. The resulting oxidative stress triggers substantial cellular damage or direct microbial cell death (Abass Huq *et al* 2022, Sofi *et al* 2022). Consequently, the impact of silver ions is instrumental in the death of bacterial and fungal cells, thereby impeding the growth and proliferation of microorganisms in water.

Furthermore, by coupling antibacterial materials with UV radiation or ozone, microorganisms in water can be effectively eliminated (Gomes *et al* 2019). This underscores the potential for augmenting the antibacterial effect with the integration of graphene oxide quantum dots alongside silver nanoparticles. Exposure to UV radiation catalyzes GOQD to produce reactive oxygen species (ROS), damaging the DNA of cells and causing harm to bacterial and fungal cell membranes through chemical reactions on the surface of GOQD (Cai *et al* 2022). This leads to heightened membrane permeability, facilitating the leakage of cellular contents and the eventual demise of microbial cells. One of the most distinctive features distinguishing graphene oxide from graphene is its functional groups (Tavakol *et al* 2020). Functional groups on graphene oxide prevent the growth and proliferation of microorganisms by changing the chemical properties of the surface, which increases the antimicrobial properties of graphene oxide (Pulingam *et al* 2021). The unique attributes of GOQD render them an optimal carrier for silver, given their nanoscale dimensions, highly hydrophilic functional surface groups, and substantial antibacterial capacity (Kumar *et al* 2022). The expansive surface area of GOQD augments their interaction with microbes, thus strengthening their antimicrobial effects. Notably, GOQD demonstrates the ability to adsorb microorganisms like bacteria and fungi onto their surfaces, which further enhances their capacity to capture and neutralize these organisms in water (Anand *et al* 2019). The versatile nature of GOQD is underscored by their efficacy against a diverse range of microbes, signifying their potential as a broad-spectrum antimicrobial agent (Ghulam *et al* 2022). The water decontamination mechanism offered by antibacterial

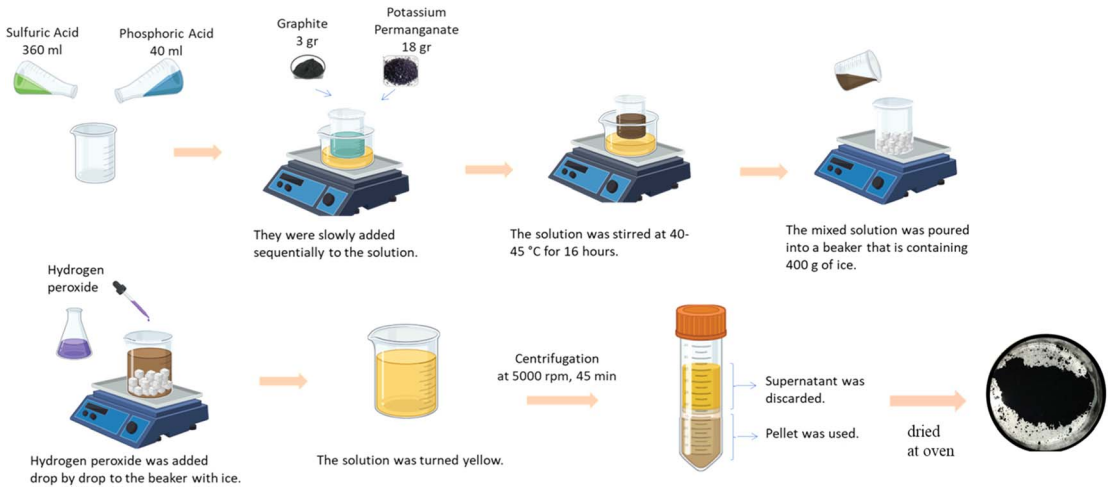


Figure 1. Synthesis of graphene oxide by hummer's method.

GOQD presents an effective means of eradicating bacteria and fungi, thus enabling water utilization for drinking.

Particularly in regions afflicted by limited water resources or water supply challenges, antibacterial products hold the promise of enabling the efficient use of water. The conservation and sustainable utilization of clean water resources are intrinsically linked to sustainability, with the judicious application of antibacterial products serving as a proactive measure to avert water resource pollution. Consequently, these products extend the usability of water derived from such resources (Long *et al* 2021).

The synergy of graphene oxide quantum dots and silver nanoparticles, with their inherent antibacterial properties, holds significant promise in both medical and industrial applications. These materials serve as potential alternatives to conventional antibiotics, opening up new avenues for the prevention and treatment of bacterial infections. The research inquiry conducted in this study explored the antibacterial efficacy of silver nanoparticles against *E. coli, S. typhi*, and *S. aureus*. Silver nanoparticles, widely recognized as effective biocides, displayed heightened antibacterial effect when coupled with GOQD.

This study, therefore, underscores the successful synthesis of graphene oxide quantum dots combined with silver nanoparticles and their antibacterial impact against *E. coli*, *S. typhi*, and *S. aureus*.

2. Experimental part

2.1. Materials and instrumentations

In this study, all chemicals used were analytical grade: Sulfuric Acid (H_2SO_4) (MERCK, 7664-93-9, Germany), Phosphoric Acid (H_3PO_4) (MERCK, 7664-38-2, Germany), Graphite, Potassium Permanganate ($KMnO_4$) (ISOLAB, 7722-64-7, Germany), Hydrogen Peroxide (H_2O_2) (30 wt%) (MERCK, 1085972500), Hydrochloric Acid (HCl) (38 wt%) (ISOLAB, 7647-01-0, Germany), Anhydrous Ethanol (ISOLAB, 64-17-5, Germany), Sodium Hydroxide (NaOH) (MERCK, 106498.1000, Germany), Silver Nitrate ($AgNO_3$) (SIGMA ALDRICH, 209139) were used as received.

The study was carried by Centrifugation (NÜVE, NF 800, Turkey), Ultrasonic Homogenizer (HINOTEK, JY96-IIN, China), Ultrasonic Bath (ISOLAB, 621.05.001, Germany), Fourier Transform Infrared spectroscopy (JASCO 4700, USA), Zeta Sizer (MALVERN INSTRUMENTS, Zetasizer Nano ZS, England), Transmission Electron Microscopy (Jeol JEM 2100 plus).

Escherichia coli ATCC 25150 and *Salmonella typhi ATCC* 14028 gram-negative bacteria and *Staphylococcus aureus ATCC* 29213 gram-positive bacteria used for this purpose were obtained from Yıldız Technical University, Bioengineering Laboratories. All chemical materials used in Antibacterial Assay were obtained from Merck Millipore.

2.2. Synthesis of graphene oxide

Graphene Oxide (GO) was synthesized by Hummer's Method (figure 1). In the reaction step, 360 ml of sulfuric acid (H_2SO_4) and 40 ml of phosphoric acid (H_3PO_4) were mixed at 200 rpm on a magnetic stirrer. For the reaction, 3 g of graphite and 18 g of potassium permanganate ($KMnO_4$) were added slowly to the prepared solution, respectively. The temperature of this mixture was set at a constant temperature of 40 °C–45 °C, then it

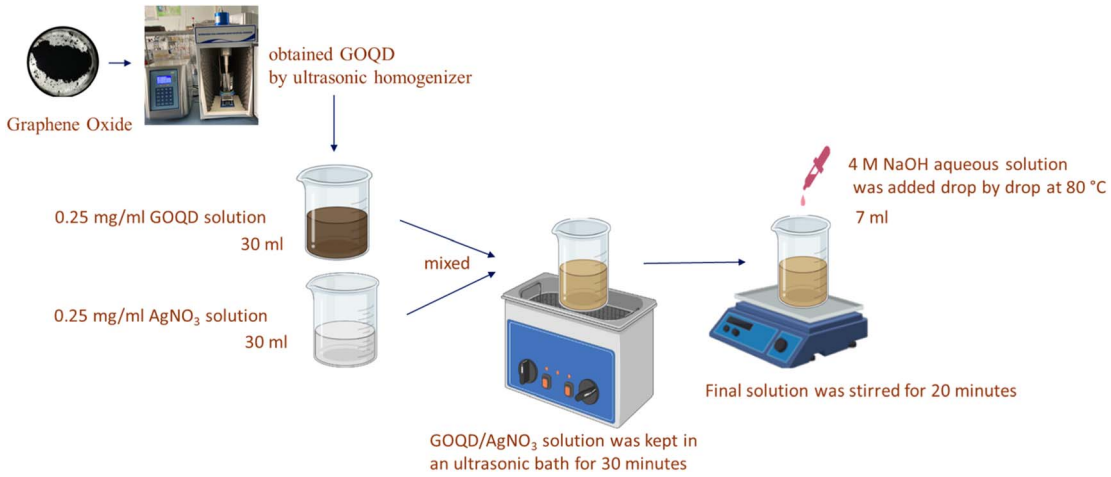


Figure 2. Obtaining silver nanoparticles in GOQD solution.

Table 1. Sonication parameters of homogenizer to obtain graphene oxide quantum dots.

Sonication Parameters	
On	6 s
Off	3 s
Duration	60 min × 5
Average Temperature	20 °C
Power	90%

was mixed for 16 h. After 16 h, this solution was transferred to a beaker that is containing 400 g of ice and mixed in the reaction quenching step. While the solution was mixed with ice, 3 ml of 30 wt% hydrogen peroxide (H_2O_2) was added drop by drop. The fact that the resulting graphite is white indicates that the reaction is perfect. If the graphite is still gray or black, the reaction is started all over again.) In the washing step, the reaction was centrifuged at 3000 rpm for 45 min. The acid supernatant was decanted to the waste box. Then, the obtained pellets were washed sequentially once with distilled water, 3 times with HCl (38 wt%), and 3 times with anhydrous ethanol by centrifugation at 5000 rpm for 45 min. The final pellet was dried in an oven.

2.3. Preparing of graphene oxide quantum dots (GOQD)

After GO was obtained, an ultrasonic homogenizer was used to create quantum dots. Using the parameters in table 1, 0.25 mg ml^{-1} GO solution prepared with distilled water was sonicated for 5 h. After 5 h, the GOQD was obtained. Samples were taken at points 1st, 3rd, and 5th.

2.4. Graphene oxide quantum dots/ silver nanoparticles (GOQD/AgNP)

30 ml of 0.25 mg ml^{-1} $AgNO_3$ solution and 30 ml of 0.25 mg ml^{-1} GOQD solution were mixed and kept in an ultrasonic bath for 30 min. Then 7 ml of 4 M NaOH aqueous solution was added to this solution drop by drop at 80 °C. And the final solution was stirred for 20 min (figure 2).

2.5. Antibacterial assay of graphene oxide quantum dots/ silver nanoparticles (GOQD/AgNP)

In this study, the antimicrobial activities of GOQD/AgNP were examined against *E. coli, S. typhi*, and *S. aureus*. Pathogens whose antibacterial activity was determined was be obtained from Yıldız Technical University Food Engineering Department Laboratory. *E. coli, S. typhi*, and *S. aureus* were activated by incubating in NB (Nutrient Broth) medium at 37 °C for 24 h, respectively.

2.5.1. Preparation of bacterial media

Bacteria concentrations 1.5×10^5 CFU/ml, 1.5×10^6 CFU/ml, 1.5×10^7 CFU/ml were prepared in three groups for each *E. coli, S. typhi*, and *S. aureus*, respectively. Bacteria was diluted by preparing the above concentrations. To detect the turbidity of the bacteria, the bacteria placed in the Spectrophotometer were graded

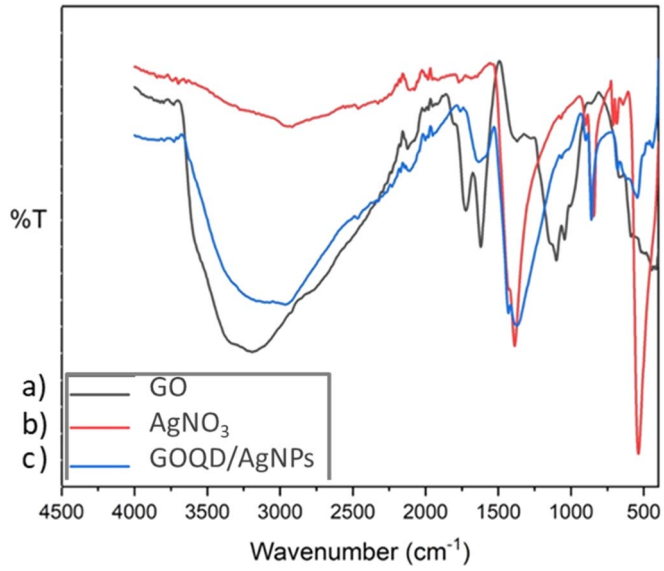


Figure 3. FTIR Spectrums of nanoparticles. a) GO, b) $AgNO_3$ c) GOQD/AgNP.

according to the McFarland criterion at a wavelength of 625 nm. According to this criterion, bacteria that were found to have a concentration of 1.5×10^7 CFU/ml were diluted twice (1.5×10^5 CFU/ml) and prepared at the desired concentration (M_2) and desired volume (V_2) according to the formula $M_1xV_1 = M_2xV_2$ (M_1: 1.5×10^5 CFU/ml). After this dilution, certain amounts of (V_1) cultures were taken for measurement from the total volume obtained, and solutions of 200 ml (V_2) each were prepared. This method was done for *E. coli, S. typhi*, and *S. aureus*.

2.6. Antibacterial assay

The agar disc diffusion method was used to determine the antibacterial activities of GOQD/AgNP mixtures containing silver nanoparticles at different concentrations against *E. coli, S. typhi*, and *S. aureus* (Abu Nayem *et al* 2020). First, these cultures on nutrient agar were transferred to nutrient broth and activated, and the bacteria were grown at 35 ± 2 °C for 24 h. Then, the cell numbers of these bacteria were adjusted according to the 0.5 McFarland standard and 100 μl bacteria were inoculated into petri dishes with nutrient agar. After the solutions of different AgNP concentrations were adsorbed on sterile paper discs with a diameter of 6 mm (30 μl), the discs were placed in nutrient agar-planted petri dishes and incubated at 35 ± 2 °C for 24 h, and the antibacterial activities were determined by measuring the diameters of the inhibition zones formed. GOQD were used for negative control in these studies and all experiments were performed in 4 replicates.

3. Results and discussions

3.1. FTIR spectra

FTIR analysis was carried out to investigate the functional groups of GOQD and AgNP (figure 3). Chemical characterization of nanoparticles was investigated using Fourier Transform Infrared (FTIR) spectroscopy (Nicholet FT-IR Spectrometer) in the range of 4000–400 cm^{-1}. Samples turned into small clusters to take data.

A broad peak is observed between 3000–3500 cm^{-1}, corresponding to the stretching and bending vibration of the OH groups of water molecules adsorbed on the GO (figure 3(a)). This peak indicates that GO has a strong hydrophilic structure. The characteristic peaks at 1727 cm^{-1} indicate the carboxyl C=O group, and the peak at 1617 cm^{-1} indicates the aromatic C=C group. The absorption peaks at 2917 cm^{-1} correspond to the stretching vibrations of CH_2. The absorption peaks at 1376 cm^{-1} indicate the stretching vibration of the C=O bond of the carboxylic acid. The presence of absorption bonds in the range of 2925 cm^{-1}, 2119 cm^{-1}, 1768 cm^{-1}, 1631 cm^{-1}, 1380 cm^{-1}, 916 cm^{-1} and 534 cm^{-1} indicates the presence of AgNP nanoparticles. There are functional groups coming from GO on the GOQD surface, which is obtained by exposing GO nanoparticles to ultrasonic waves. The presence of hydroxyl groups and oxygen groups on the surface of GOQD makes GOQD suitable for modification with AgNP. The 3500–2500 cm^{-1} broad band and the 1376 cm^{-1} peak of GOQD/AgNP may prove that there is an interaction between AgNP and GOQD by creating a consistent chemical bond or electrostatic attraction (figure 3(c)) (Rattana *et al* 2012, Thirunavoukkarasu *et al* 2013, Shao *et al* 2015).

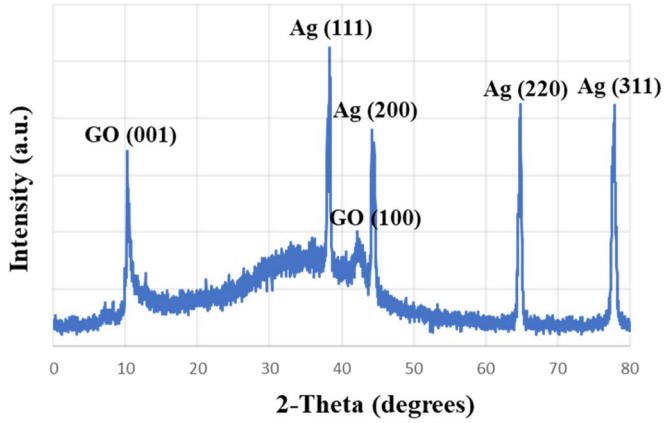


Figure 4. The XRD analysis of GOQD/AgNP.

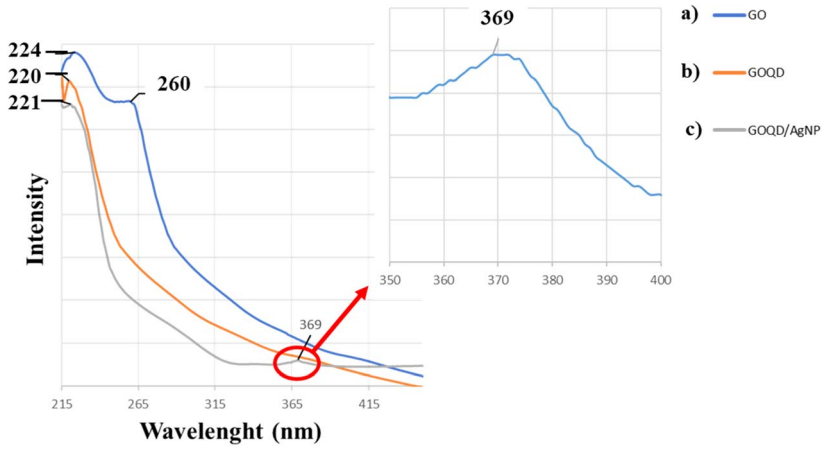


Figure 5. UV–vis absorption spectra (a) GO, (b) GOQD, (c) GOQD/AgNP.

3.2. XRD analysis

In x-ray diffraction analysis, characteristic peaks for GO appeared as a sharp peak at $2\theta = 10.5524°$ corresponding to (001) plane (Oktay *et al* 2023). Therefore, when looking at the figure 4, the weak peak at 10.1585° was attributed to GO. GO had prominent peaks at around 42° corresponding to (100) reference plane. This characteristic peak is due to turbostratic disorder of carbon material. Looking at the GOQD/AgNP results, the strongest peaks were seen at 38.3112°, 44.3258°, 64.7149° and 77.7380° (figure 4). The x-ray diffraction pattern of obtained AgNP is shown in figure 4. XRD peaks are angled at 38.3, 44.2, 64.7, and 77.7 corresponding to (111), (200), (220) and (311) *hkl* planes of AgNP for the face-centered cubic silver (Das *et al* 2021). Compared to the literature, these peaks were characteristic peaks of silver nanoparticles (Agasti and Kaushik 2014). The amount of material affects the intensity and width of the XRD peaks. This is the reason why the characteristic peaks of silver nanoparticles have higher peak intensity than the characteristic peaks of graphene oxide quantum dots. The use of graphene oxide quantum dots in smaller amounts than silver nanoparticles in the GOQD/AgNP composite resulted in weaker peaks (Zhao *et al* 2020). As a result, the characteristic peaks were obtained by XRD show that the GOQD/AgNP composite was successfully obtained.

3.3. UV–vis spectroscopy

UV–vis spectroscopy was used to show the formation of AgNP on GOQD nanocomposite. UV–vis absorption spectra of GO, GOQD, and GOQD/AgNP composites. As shown in figure 5(a), two characteristic peaks were observed in the UV–vis spectrum of GO which are a maximum at 224 nm and a shoulder at about 260 nm (Yang *et al* 2012). A signal at 224 nm which ascribes the π–π^* transitions of the aromatic C–C bonds and a shoulder at 260 nm, which is derived from the n–π^* transitions of the C═O bonds are shown. The the characteristic peak of obtained GOQD after sonication can be seen at 220 nm in the UV–vis spectra (figure 5(b)) (Yan *et al* 2014). After

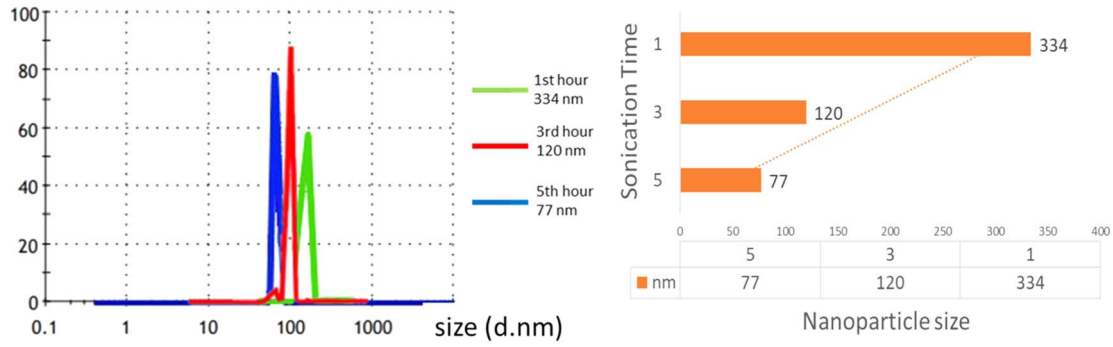


Figure 6. Size of GO nanoparticles after the 1st, 3rd, and 5th hour.

AgNP modification of GOQD, the characteristic peak of GOQD/AgNP was visible at 369 nm (Yang *et al* 2020). It was observed that typical absorption peak at 221 nm, which is speculated to due to the absorption of the graphene oxide quantum dot structure. The magnified in figure 5(c) shows a visible absorption peak at around 369 nm for GOQD/AgNP composite, which is attributed to the Localized Surface Plasmon Resonance (LSPR) absorption of Ag nanoparticles (Ran *et al* 2014, Shao *et al* 2015, Das *et al* 2021).

3.4. Zeta potential

The particle size of the graphene oxide quantum dot samples we obtained was examined with the Zeta Sizer device. For measuring, the solution was diluted.

According to the results obtained, the particle sizes of the GOQD sample after 1 h, 3 h and 5 h sonication times are 334 nm, 120 nm and 77 nm, respectively (figure 6). As can be seen here, particle sizes compatible with the literature were obtained in the GOQD samples (Tian *et al* 2018).

3.5. TEM analysis

Figure 7 shows TEM images of graphene oxide and fragmented GO nanoparticles. As seen in figure 7(a), the layer-by-layer image of graphene oxide nanosheets is clearly illustrated (El Hadki *et al* 2021). The obtained GO nanosheets were broken into small fragments using ultrasonic sound waves. By the end of the first hour of ultrasonication of GO, the nanosheets were fragmented, and their size was greater than 100 nm (figure 7(b)). Subsequently, the GO nanosheets were exposed to ultrasonication for 3 h. At the end of 3 h, structures with dimensions smaller than 100 nm were observed, as shown in figure 7(c). However, these structures were still not small enough to be classified as graphene oxide quantum dots. GOQDs were achieved by subjecting GO nanosheets to ultrasonic sound waves for a total of 5 h (figure 7(d)). Figures 7(d)–(f) displays TEM images of GOQD with different magnifications. Figure 7(f) validates that the size of the GOQD obtained after 5 h was sufficiently reduced. In figure 7(f), it is stated that the average dimensions of the GOQD are approximately 10 nm. The resulting TEM image clearly demonstrates that the quantum dots are smaller than 20 nm. Thus, TEM images confirm that as the exposure time of graphene oxide nanosheets to sound waves through ultrasonication increases, their size decreases, ultimately resulting in the formation of graphene oxide quantum dots (figures 7(b)–(d)). These results also support the time-dependent reduction in particle sizes as shown in figure 6.

Figures 8(a) and (b) indicate TEM images of GOQD/AgNP at different magnifications. It is observed that the diameter of graphene oxide quantum dots increases with the presence of silver nanoparticles. After GOQD was obtained, they were treated with silver nitrate, and silver nanoparticles were formed *in situ*. Upon examining the TEM images, it was observed that silver nanoparticles accumulated on the GOQD (figure 8). TEM image shows AgNPs were embedded on the surface of GOQD and displayed multi-twinned structures. The darker regions in figure 8(a) reveal silver nanoparticles growing on GOQD. It has been demonstrated that there is an interaction with AgNP facilitated by different groups on GOQD. The difference in charges between GOQD and AgNP may have caused them to attract each other, leading to the accumulation of AgNP on GOQD (Bharathi *et al* 2017, Chiu *et al* 2020, Garg *et al* 2020).

3.6. Antibacterial assay

The antibacterial activities of GOQD/AgNP mixtures containing different concentrations of AgNP against different types of gram-negative and gram-positive bacteria are shown in table 2. According to this table, it was understood that the GOQD used as negative controls did not show any antibacterial activity. The greatest inhibition zone for each bacterial species was seen in the GOQD/AgNP mixtures with the highest concentration

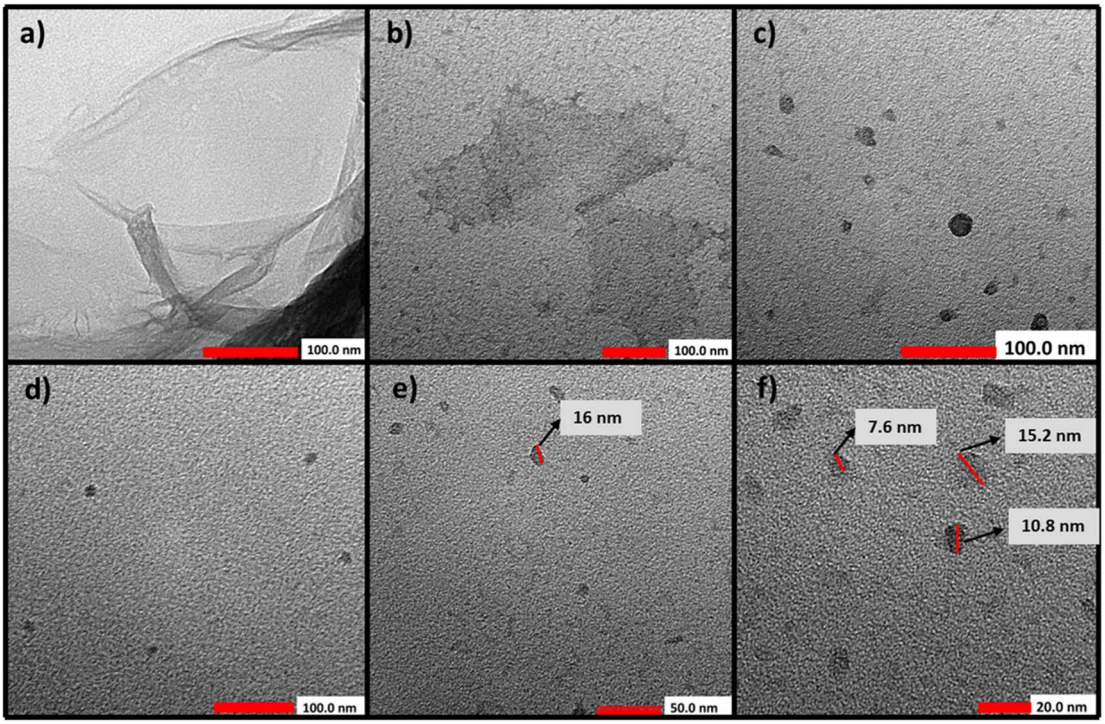


Figure 7. TEM images of (a) GO nanosheets, (b) GO at the 1st hour, (c) GO at the 3rd hour, (d), (e), (f) GOQD at the 5th hour at different magnification.

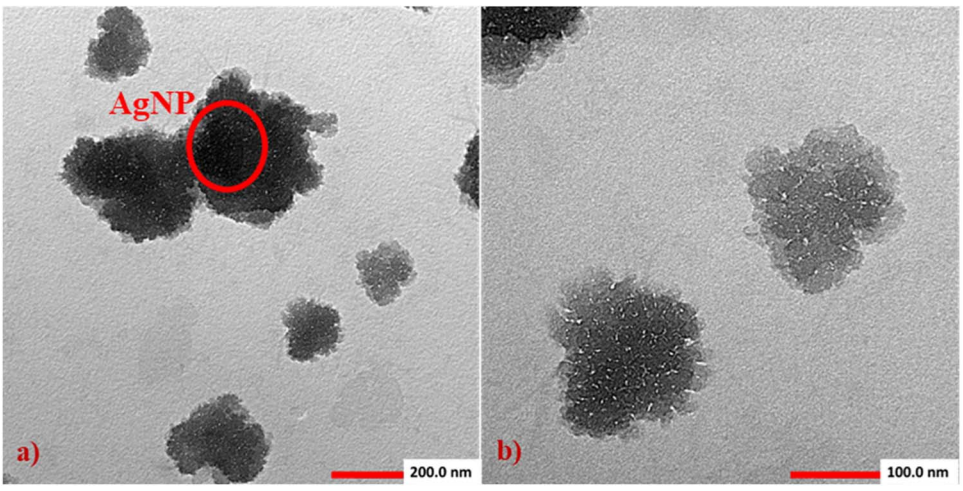


Figure 8. TEM images of GOQD/AgNP at different magnification.

of AgNP. Because AgNP show high antibacterial activity, this has been proven in many studies in the literature (Chen *et al* 2017). The most sensitive bacterial species to GOQD/AgNP mixtures is *S. typhi*, while the most resistant bacterial species is *S. aureus*. The diameter of the highest inhibition zone for *S. typhi* was measured as 11.75 ± 0.96 mm, while for *S. aureus* this value was measured as 9.88 ± 0.25 mm (figure 9). The reason for this may be the differences in the cell walls of these bacteria (Huang *et al* 2020). *E. coli* and *S. typh*i bacteria used in this study are gram negative bacteria and have a thin peptidoglycan layer on their cell walls. For this reason, nanoparticles can penetrate into the bacterial cell more easily and inhibit the bacteria more easily. Gram-positive bacteria, such as *S. aureus*, have a thicker peptidoglycan layer on their cell walls and, as a result, they are more resistant to these materials due to less concentration of AgNP penetration into the cell (Gudkov *et al* 2022).

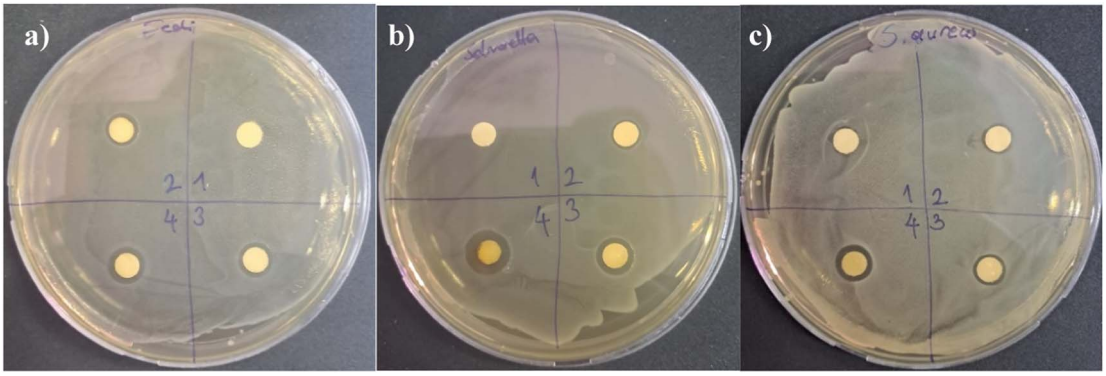


Figure 9. Antibacterial activity of GOQD/AgNP on (a) *E. coli* (b) *S. typhi* (c) *S. aureus*.

Table 2. Inhibition diameters (mm) of GOQD/AgNP samples against different pathogenic bacteria.

	E. coli	*S. typhi*	*S. aureus*
Negative Control	—	—	—
1. concentration	7.13 ± 0.25^{C}	7.75 ± 0.5^{C}	7.38 ± 0.48^{C}
2. concentration	8.88 ± 0.25^{B}	9.25 ± 0.5^{B}	8.25 ± 0.29^{B}
3. concentration	10 ± 0.41^{A}	11.75 ± 0.96^{A}	9.88 ± 0.25^{A}

Data are presented as means ± standard deviations (n = 4).
A–C: Different superscript uppercase letters show differences between the GOQD/AgNP samples within each bacteria ($p < 0.05$).

4. Conclusion

In this study, silver nanoparticle with graphene oxide quantum dots (GOQD/AgNP) was prepared to determine their antibacterial activity. According to the results, the GOQD was obtained successfully by ultrasonication. TEM images show the silver nanoparticles were embedded on the graphene oxide quantum dots by *in situ* method. The antibacterial activities of GOQD/AgNP mixtures containing different concentrations of AgNP against different types of gram-negative and gram-positive bacteria. it was understood that the GOQD used as negative controls did not show any antibacterial activity. The greatest inhibition zone for each bacterial species was seen in the GOQD/AgNP mixtures with the highest concentration of AgNP. The most sensitive bacterial species to GOQD/AgNP mixtures is *S. typhi*, while the most resistant bacterial species is *S. aureus*.

The pressing global issue of water contamination by bacteria and fungi necessitates innovative solutions for water purification. The deployment of nanomaterials, specifically graphene oxide quantum dots and silver nanoparticles, offers a promising avenue for addressing this challenge. These materials, owing to their unique properties and synergistic effects, have the potential to play a pivotal role in the mitigation of waterborne diseases, environmental protection, and the sustainable utilization of clean water resources. By effectively eliminating microorganisms in water, antibacterial materials enhance the safety and cleanliness of water sources, ensuring their availability for future generations. In conclusion, the combination of graphene oxide quantum dots and silver nanoparticles represents an exciting advancement with applications in both medical and industrial domains, heralding a new era in the prevention and treatment of bacterial infections.

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Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

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