Egyptian Journal of Aquatic Biology & Fisheries
Zoology Department, Faculty of Science,
Ain Shams University, Cairo, Egypt.
ISSN 1110 – 6131
Vol. 29(5): 1 – 13 (2025)
www.ejabf.journals.ekb.eg

Degradation of Bacteria for Aquatic Wastewater Treatment in a Nanoparticles TiO_2 and ZnO Coated Photo Catalytic Reactors Illuminated by Solar Light ZnO, TiO_2

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ARTICLE INFO

Article History:
Received: June 24, 2025
Accepted: Aug. 12, 2025
Online: Sep. 3, 2025

Keywords:
Solar disinfection,
Nanoparticles,
Water disinfection,
Environmental remediation

ABSTRACT

Access to clean and safe drinking water is a fundamental human right, essential for sustaining life and promoting public health. This highlights the urgent need for innovative technologies to address water quality challenges. Nanotechnology has shown great promise in this field due to the unique properties of nanomaterials, which can be harnessed to enhance water treatment performance. This study explored water pollution treatment using reactors coated with nanomaterials and exposed to direct sunlight to activate their catalytic properties. The approach was developed as an alternative to conventional disinfectants such as chlorine—widely known for its harmful and carcinogenic effects—or ozone, which, while effective, is costly. An experimental methodology was applied using water samples collected from wastewater treatment plants. The efficiency of nanomaterials in eliminating bacteria, particularly *Escherichia coli* and *Bacillus*, was assessed alongside their influence on selected physicochemical parameters, including pH, electrical conductivity, and total soluble solids. Absorbance curves were measured before and after treatment with nanoparticle-coated reactors. The curves revealed no abnormal peaks or spectral changes, confirming the stability of the nanomaterials within the treatment system and their lack of mixing with the treated water. No significant changes in pH were observed, while only slight variations in electrical conductivity were recorded. Overall, the results demonstrate that the use of nanomaterials in combination with solar energy provides a safe, efficient, and sustainable technology for water treatment. This approach is particularly valuable for resource-limited settings and remote areas, where it can improve water quality and reduce bacterial contamination risks without dependence on harmful chemicals.

INTRODUCTION

In recent decades, the world has faced increasing challenges in water resource management due to rapid population growth, industrialization, and agricultural expansion, leading to unprecedented levels of water consumption. Although water covers more than 71% of the Earth's surface, less than 1% of it is fresh water available for drinking, largely due to pollution and environmental change **(Muhammad Ali, 2023)**. While centralized drinking water treatment systems are effective in urban areas, they are often inaccessible in rural and remote communities. Consequently, household water treatment technologies have emerged as vital tools for reducing the spread of waterborne diseases **(Hunter, 2009)**. However, many of these technologies are constrained by limited efficiency or high energy demand **(WHO, 2017)**, highlighting the urgent need for sustainable and effective alternatives.

Recent studies demonstrate that nanotechnology offers promising solutions to water treatment challenges. For example, **Dufner *et al.* (2025)** eliminated bacterial contamination using titanium oxide-coated reactors activated by sunlight, while **Al-Taghlabi (2024)** emphasized the impact of economic activities on river pollution in Iraq, with the Kufa River as a case study. In Iraq, water quality challenges are further intensified by pollution, reduced water levels, and increasing demand, necessitating intensified efforts to monitor pollutants, assess their impacts, and develop effective treatment approaches **(Al-Saffawi & Al-Maathi, 2014, 2017)**.

Nanomaterials are particularly attractive for this purpose due to their unique physical and chemical properties, such as high surface-to-volume ratios, enhanced reactivity, and high adsorption capacity. These features make them efficient candidates for removing pollutants from water, offering new opportunities to improve water quality in efficient and sustainable ways.

The water resources of Iraq, particularly the Tigris and Euphrates rivers and their tributaries, face severe pressures from sewage discharge, industrial waste, and unregulated development. For instance, untreated sewage has been released into the Khosr stream in Mosul, resulting in the complete disappearance of aquatic life compared to the clear, fish-rich waters observed in the 1970s **(Al-Mashhadani, 2019)**. The Tigris River continues to receive 350– 400m³ of wastewater daily **(Mustafa & Jankir, 2007)**. Water treatment plants along the river vary in efficiency, influenced by differences in geographic location, production capacity, and chemical additives **(Al-Naimi & Al-Nima, 2015)**. However, the city of Mosul still struggles with water quality issues, compounded by aging treatment infrastructure **(Abdul-Baqi, 2020)**. Excessive reliance on chlorine for water purification has also raised health concerns, as high concentrations can cause respiratory and skin diseases, eye irritation, and corrosion of pipelines, leading to the release of toxic heavy metals such as lead into drinking water.

Objectives of the study

1. To investigate the biological treatment of water using reactors coated with nanomaterials, activated by direct sunlight to exploit their catalytic properties. This approach aims to improve pollutant removal rates and enhance overall water quality.
2. To evaluate the effect of nanomaterials on biodegradation efficiency and analyze changes in water’s physical and chemical properties following treatment. The study also examines factors influencing treatment performance, including nanomaterial type, concentration, and environmental conditions.

Description of the study area

The study was conducted at two sites in the city of Mosul, located in northern Iraq (36°21'09.7"N, 43°07'32.5"E).

1. Qarah Saray Estuary (36°21'09.7"N, 43°07'32.5"E)
This estuary, situated near the Fifth Bridge, flows directly into the Tigris River and is one of the main estuaries on Mosul's right bank. Its water consists of a mixture of rainwater and sewage. The box sewer extends approximately 1.4km, passing through Ibn al-Atheer Station, Qasim al-Khayat Roundabout, and the Al-Shifa neighborhood. It connects to three main sewage pathways:

- **First Path:** Originates from the Pepsi plant, extends ~1 km.
- **Second Path:** Begins in the Zanjili area, passing through the Al-Siha, Al-Rifai, and Al-Islah Al-Zira'i neighborhoods, and the Yarmouk Roundabout, covering ~4 km.
- **Third Path:** Connects to the Bab Sinjar pumping station, which lifts sewage from the Wadi Akab industrial area, part of the Al-Borsa area, and the Fifth Bridge tunnels, with a length of ~2 km (Nineveh Sewerage Directorate).

2. Al-Maidan Estuary (36°20'43.1"N, 43°08'13.6"E)
This major estuary in Mosul's old city (right bank) is used for draining rainwater and sewage. It begins at Ras Al-Jada, passes through Khazraj, the Sa'a, Al-Sarkhana, Al-Sha'areen Market, and the Fish Market, before discharging below the Old Bridge. Its total length is ~1.7 km (Nineveh Sewerage Directorate).

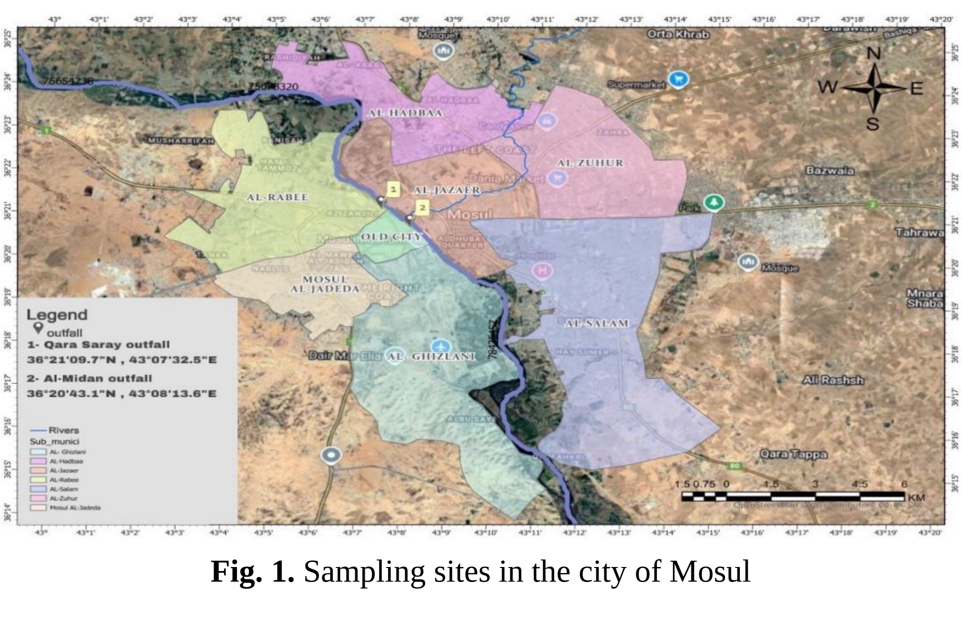

Fig. 1. Sampling sites in the city of Mosul

MATERIALS AND METHODS

Reactor preparation

Nanomaterials manufactured by Sky Spring Nanomaterials (USA) were used in this study, with a high purity of 99% and particle sizes ranging from 10– 30nm, providing a large specific surface area and high chemical activity. To enhance nanoparticle stability in the reactors and prevent agglomeration, silane coupling agents were applied. Safe transparent pigments were supplied by ONAY BOYA (Turkey).

For tank preparation, the nanomaterials were mixed with the transparent pigment to ensure effective adhesion to the tank surface. The coated tanks were left to dry for 48 hours to ensure complete curing and to prevent mixing of the coating with water during subsequent use.

After curing, water samples were collected from the Meydan and Qarah Saray estuaries, filtered through medical gauze, and placed in the nanomaterial-coated tanks. Samples were then exposed to direct sunlight for 3 hours at midday. During the experimental period, ambient temperatures ranged between 10 and 25°C, while solar radiation intensity varied from 700 to 950W/ m² (Figs. 1, 2).

Fig. 2. The position of the reactor coated with nanomaterials under direct sunlight

Sample collection methods

Surface water samples were collected from two contaminated sites using clean 20L plastic containers. Samples were transported to the laboratory under refrigerated conditions (< 4°C) to preserve the biological integrity of bacterial communities. Collection was carried out weekly between November 5, 2024, and March 8, 2025, with three replicates obtained per sampling event.

In the laboratory, samples were divided into three experimental groups:

1. Tanks coated with nanomaterial type 1.
2. Tanks coated with nanomaterial type 2.

3. An uncoated control tank (for comparison of treatment with and without nanomaterials).

Prior to placement in the tanks, water samples were filtered through medical gauze to remove suspended solids. Physical and biological variables were then recorded at the following stages:

- Before filtration with gauze.
- After filtration with gauze.
- 30 minutes after pouring samples into the tanks.
- 2 hours after pouring samples into the tanks.
- 3 hours after pouring samples into the tanks.

RESULTS

1. Comparison between the two nanomaterials

Water samples were treated to compare the effectiveness of zinc oxide (ZnO) and titanium dioxide (TiO_2) in biological treatment. Samples were divided into two groups of tanks, with each group coated with one of the two nanomaterials. The concentrations of ZnO and TiO_2 used in the experiment are presented in Tables (1-3):

Table1. Comparison between the two nanomaterials

Zinc oxide (ZnO) reactor	Titanium oxide (TiO_2) reactor
(Control)	(Control)
10mg/ml concentration	10mg/ml concentration
15mg/ml concentration	15mg/ml concentration

At the end of the exposure period, water samples were collected in sterile test tubes to maintain sample integrity and prevent external contamination. The samples were then transported to the laboratory for microbiological culture and diagnosis.

For bacterial enumeration, 1mL of treated water was inoculated into agar medium using the pour plate method. The sample was mixed with warm, sterile liquid agar (approximately 45°C), poured into sterile Petri dishes, and allowed to solidify under aseptic conditions.

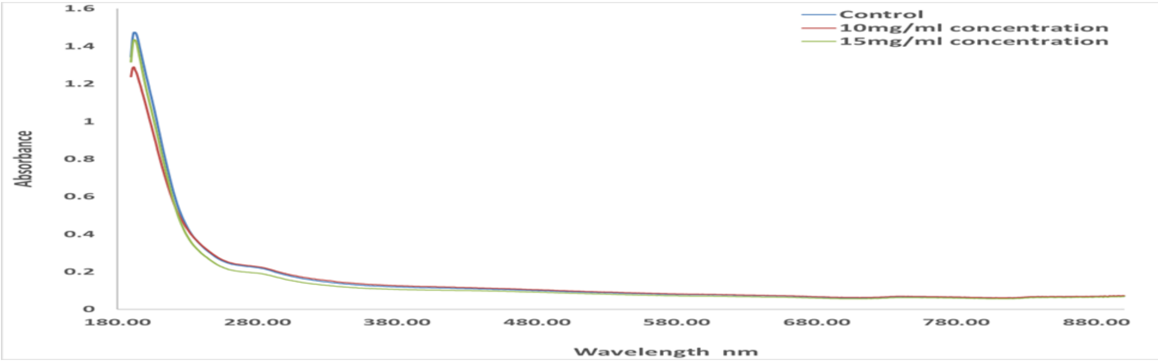

Fig. 3. UV spectrum of titanium oxide after one hour

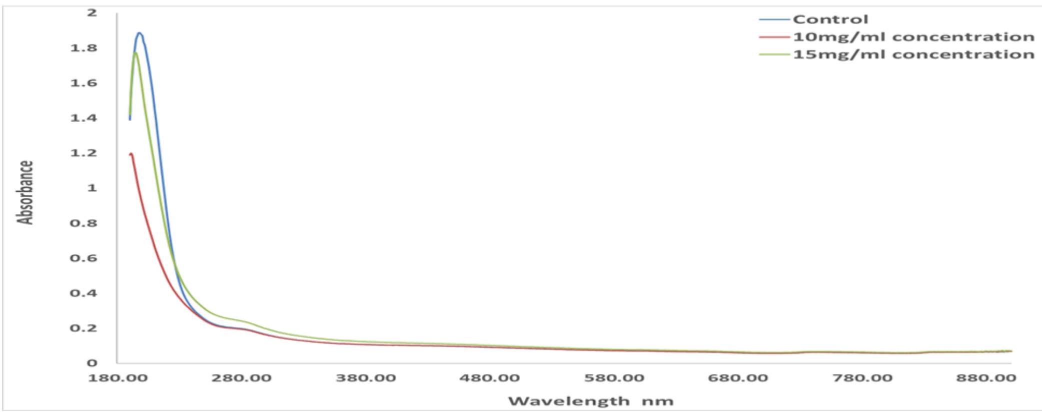

Fig. 4. UV spectrum of titanium oxide after three hours

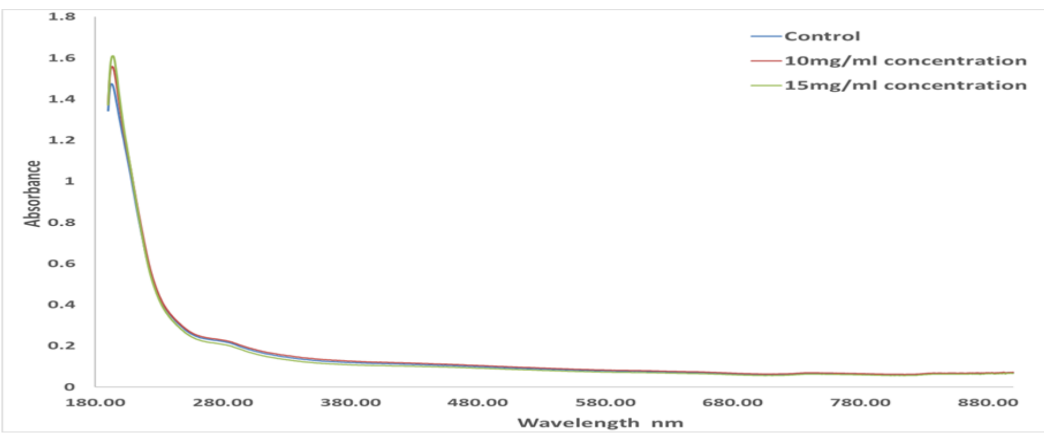

Fig. 5. UV spectrum of zinc oxide after one hour

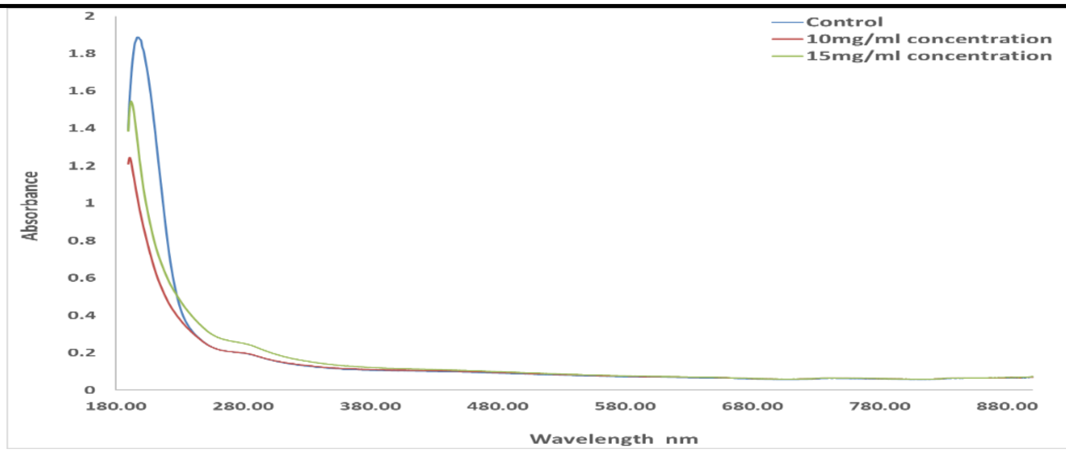

Fig. 6. UV spectrum of zinc oxide after three hours

Table 2. Total number of bacteria after one hour of treatment

Sample Location	Concentration(mg/ml)	TiO_2	ZnO
Qara Saray outfall	Control	more 300	more 300
	10	45	58
	15	18	38
Al-Midan outfall	Control	more 300	more 300
	10	6	9
	15	2	2

Table 3. Total number of bacteria after three hours of treatment

Sample Location	Concentration(mg/ml)	TiO_2	ZnO
Qara Saray outfall	Control	more 300	more 300
	10	10	35
	15	6	12
Al-Midan outfall	Control	more 180	more 180
	10	3	7
	15	0	2

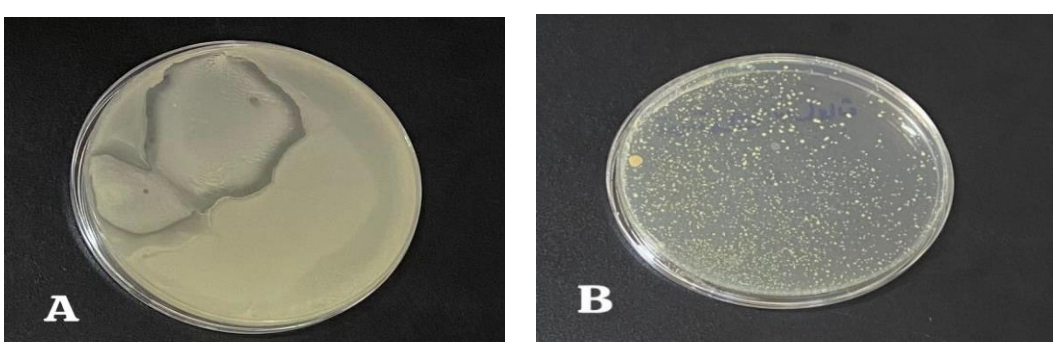

Fig. 7. Bacterial growth on the nutrient medium agar **(A)** Field control **(B)** Kara Saray control

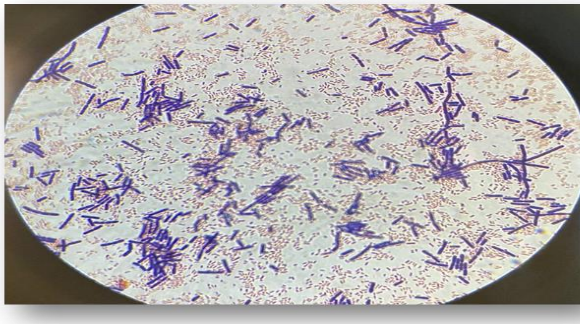

Fig. 8. Microscopic examination after staining with Gram stain

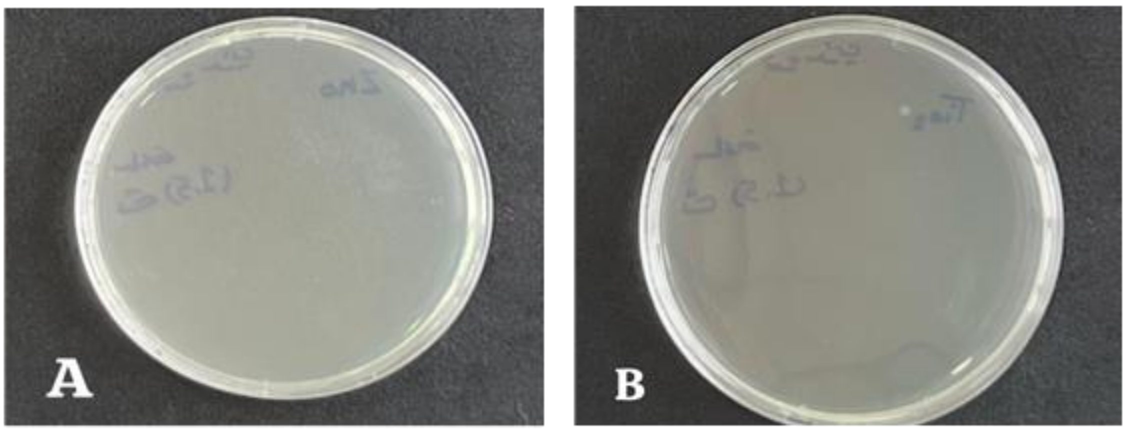

Fig. 9. Killing of bacterial cells by reactors **A:** ZnO at a concentration of 15mg/ ml; **B:** (TiO_2) at a concentration of 15mg/ ml

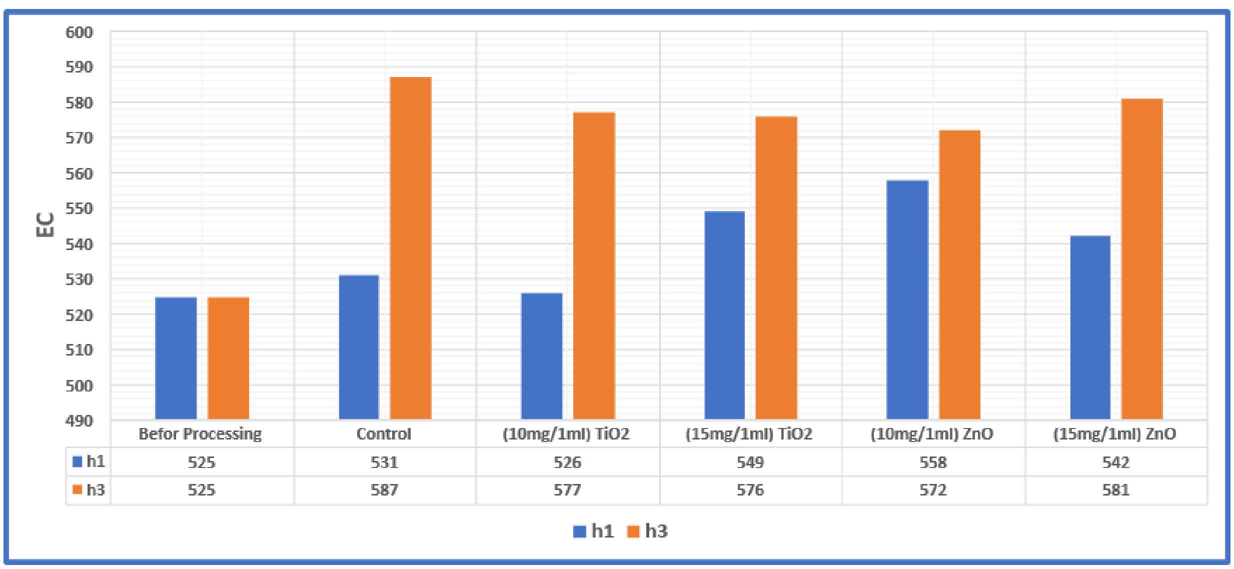

Fig. 10. EC values according to exposure time and reactant concentrations

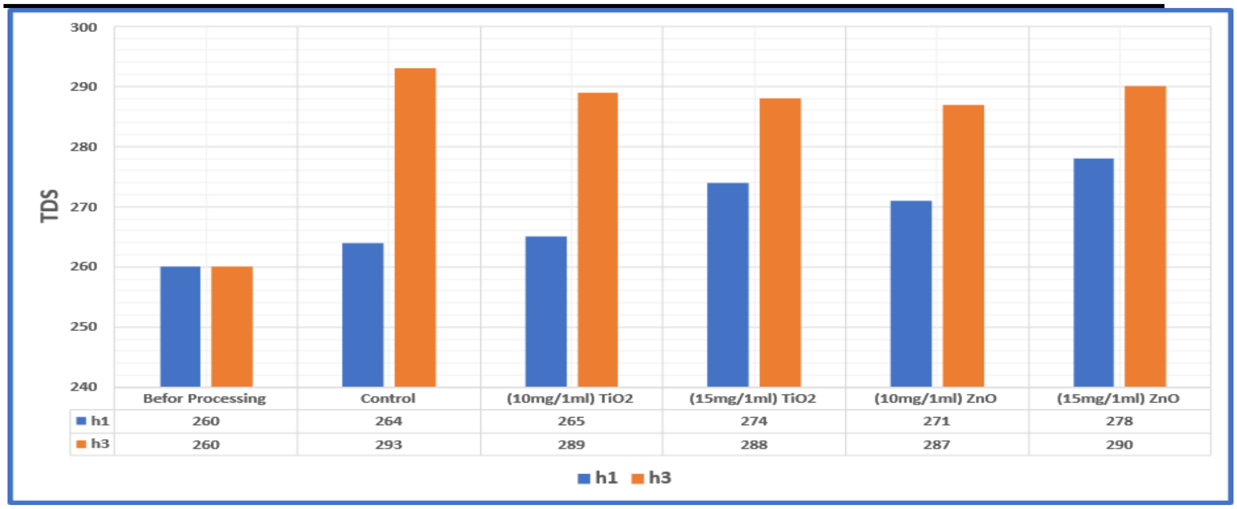

Fig. 11. TDS concentrations according to exposure time and reactor concentrations

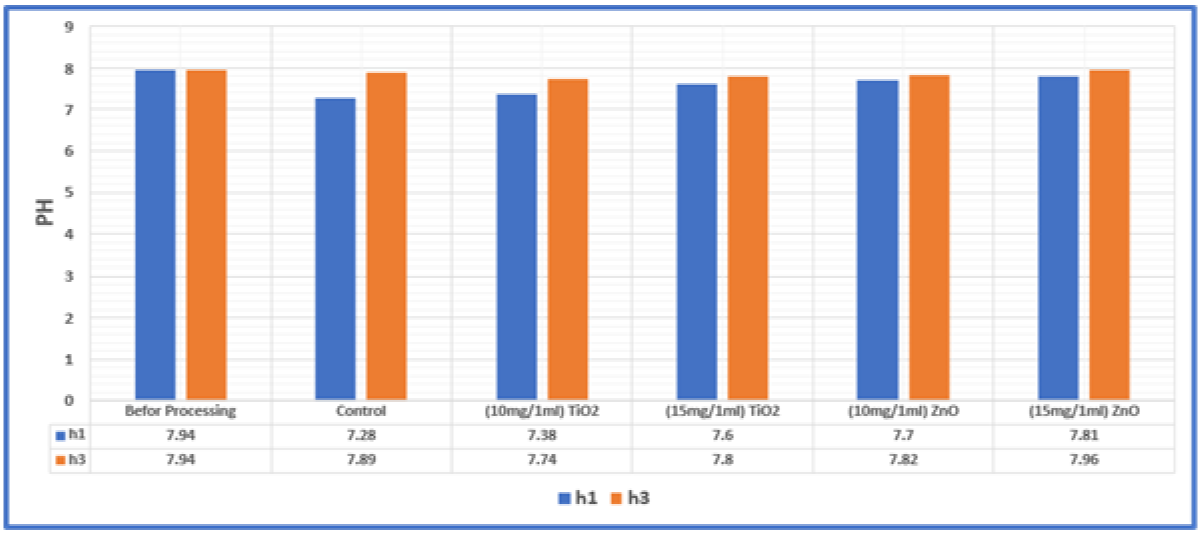

Fig. 12. Acid function values according to exposure time and reactant concentrations

DISCUSSION

Identification of nano-titanium oxide using UV-Vis spectroscopy

Figs. (4–5) show the absorption spectrum of TiO_2 at concentrations of 10–15mg/mL under sunlight exposure for one and three hours. The absorbance curves showed no new peaks, confirming the absence of free nanoparticles in the reactors. Absorption intensity decreased gradually with increasing TiO_2 concentration, indicating that the nanomaterial was effectively immobilized on the reactor surface and not migrating into the water. This suggests that TiO_2 does not alter water quality or pose risks to public health.

The high stability of TiO_2 enhances the efficiency of this technology, supporting its safe application in water treatment. By utilizing solar energy, this method not only eliminates pollutants but also prevents their release into the environment, making it an environmentally friendly and sustainable approach. These results are consistent with the findings of **Dufner *et al.* (2025)**.

UV–Vis identification of zinc oxide (ZnO) nanoparticles

Figs. (6–7) illustrate the absorbance of ZnO at concentrations of 10– 15mg/ mL under sunlight exposure. Absorbance values remained within the normal range with no new peaks or unusual spectral behavior, confirming that nanoparticles were stable, did not dissolve, and remained securely fixed in the reactors. Stability was maintained even after extended sunlight exposure, confirming ZnO's low solubility and environmental safety.

These results align with **Amin and Erfan (2025)**, who reported that ZnO nanoparticles tend to aggregate and stabilize in solution with low solubility at neutral pH, making them a safe option for large-scale water treatment applications.

Biological properties

Total bacterial count (TBC) one hour after treatment

Results showed a reduction in bacterial count after one hour of treatment compared to the control, though the decrease was more pronounced after three hours.

- **Qarah Saray Outfall**
  - Control: >300 cells/mL.
  - TiO_2 (10 mg/mL): 45 cells/mL.
  - TiO_2 (15 mg/mL): 18 cells/mL.
  - ZnO (10 mg/mL): 10 cells/mL.
  - ZnO (15 mg/mL): 38 cells/mL.
    → TiO_2 outperformed ZnO at this site.
- **Al-Midan Outfall**
  - Control: >300 cells/mL.
  - TiO_2 (10 mg/mL): 6 cells/mL.
  - ZnO (10 mg/mL): 9 cells/mL.
  - TiO_2 and ZnO (15 mg/mL): 2 cells/mL.
    → Both nanomaterials were highly effective, especially at 15mg/ mL.

The higher contamination and complex industrial waste at Qarah Saray likely hindered catalytic reactions, while Al-Midan's mainly organic pollutants were more responsive to nanomaterial treatment. These results (Table 8) confirm that nanomaterials reduce bacterial counts even after one hour, with TiO_2 showing overall stronger performance than ZnO.

Total bacterial count (TBC) three hours after treatment

After three hours, bacterial counts decreased substantially compared to controls:

- **Qarah Saray Outfall:**
  - Control: >300 cells/mL.
  - ZnO (15 mg/mL): 6 cells/mL.

- TiO_2 (15 mg/mL): 3 cells/mL.

- **Al-Midan Outfall:**
  - Control: >180 cells/mL.
  - ZnO (15 mg/mL): 2 cells/mL.
  - TiO_2 (15 mg/mL): 0 cells/mL (complete removal).

The effectiveness of TiO_2 is likely due to its superior photocatalytic properties, generating hydroxyl radicals (•OH) and other reactive oxygen species that damage bacterial cell walls. Differences between sites reflect variations in pollutant type, source, and concentration. These findings (Table 9) confirm the significant antibacterial potential of nanomaterials, particularly TiO_2, consistent with **Barnes *et al.* (2013)**.

Microscopic examination

Microscopic examination following Gram staining confirmed these results. Control samples showed a mixture of Gram-negative short rods and Gram-positive long rods (Fig. 11). In contrast, nanomaterial-treated samples revealed complete bacterial elimination across concentrations (Fig. 12). This aligns with total bacterial count results, validating the effectiveness of TiO_2 and ZnO in disinfection **(Jawetz *et al.*, 2019)**.

Physical properties

Electrical conductivity (EC)

EC values ranged between 526 and 587µS/ cm. The lowest EC was recorded at 10mg/ mL TiO_2 after one hour (526µS/ cm), while the highest was in the control after three hours (587µS/ cm) (Fig. 13). Increases in EC are attributed to high salt content in sewage water **(Al-Khabouri, 2023)**, whereas decreases reflect dilution effects from rainfall **(Al-Taie, 2022)**.

Total dissolved solids (TDS)

TDS values ranged from 264 to 293mg/ L. The lowest was observed in the control group at one hour (264mg/ L), while the highest was in the control group after three hours (293mg/ L) (Fig. 14). As expected, TDS values correlated directly with EC **(Bhat *et al.*, 2018)**.

Chemical properties

pH:

pH values remained stable, ranging from 7.28 to 7.96 (Fig. 15). These values fall within Iraqi environmental regulations for river discharge (6.0–9.5) and are consistent with **Al-Hadidi (2024)**.

Limitations

Although this study demonstrates the effectiveness of nanomaterials for water treatment, it is subject to limitations.

1. Experiments were conducted under specific environmental and solar conditions in Mosul, which may limit generalizability to other regions.
2. Only two nanomaterials (TiO_2 and ZnO) were tested; other nanoparticles or composites may perform differently.

3. Long-term environmental and health effects of potential nanoparticle residues were not assessed.
4. Financial and logistical constraints restricted sample size and experimental duration, limiting conclusions about scalability.

CONCLUSION

This study demonstrates the effectiveness of zinc oxide (ZnO) and titanium dioxide (TiO_2) nanomaterials, when combined with solar exposure, in reducing bacterial contamination in polluted water sources. The treatment significantly lowered total bacterial counts, particularly *Escherichia coli* and *Bacillus* spp., without causing adverse changes in pH, electrical conductivity, or TDS levels. Among the tested nanomaterials, TiO_2 showed superior antibacterial performance compared to ZnO.

These findings suggest that solar-assisted nanomaterial reactors represent a safe, eco-friendly, and cost-effective alternative to conventional chemical disinfectants such as chlorine. Given their effectiveness and simplicity, this technology holds strong potential for deployment in remote or resource-limited areas, offering a practical solution to improve water quality and to reduce the risk of waterborne diseases.

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