Solar water disinfection using reactants such as titanium dioxide (TiO2) and zinc oxide (ZnO)

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Abstract

Access to clean and safe drinking water is a basic human right, essential for sustaining life and promoting public health. This necessitates the exploration of new technologies. Nanotechnology has emerged as a new strategy for water purification, leveraging the unique properties of nanomaterials to address this challenge. This study addresses the problem of water pollution by using a reactor coated with nanomaterials, exposing it to direct sunlight to leverage its catalytic properties to enhance biological treatment performance. This research is part of the quest for alternative and safe solutions for water treatment, away from traditional chemicals such as chlorine, which are carcinogenic and harmful to public health, in addition to the high costs of other disinfectants such as ozone. The study was conducted using water samples taken from the Al-Maidan estuary in the Tigris River. Samples were collected weekly from November 5, 2024, to May 19, 2025, with three replicates per sample. The study included evaluating the efficiency of nanomaterials in removing bacteria, in addition to analyzing the effect of these materials on some chemical properties of water, such as ions (chloride, sulfate, nitrate, phosphorus), as well as hardness. The results showed a sharp decrease in the total bacterial count (T.B.C), with the lowest number reaching (0 cells/ml) in the treated samples, while the number exceeded (300 cells/ml) in the control tanks. The effect of titanium oxide was found to be more effective than zinc oxide. Regarding chemical properties, the results showed a stable chloride ion concentration, reaching (74 mg/L), a slight decrease in phosphorus values, and slightly increased sulfate and nitrate values. Meanwhile, the total hardness and the hardness of calcium and magnesium were relatively stable, indicating that the nanomaterials had a greater effect on bacterial pollutants than ions and hardness. These results confirm that the use of nanomaterials in combination with solar energy represents a promising and effective technology for water treatment, particularly in resource-limited and remote environments. It can contribute to improving water quality and reducing the risk of bacterial contamination without relying on harmful chemicals.

Keywords: Water treatment, photocatalysis, nano oxides, reactive oxygen species, environmental remediation

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Introduction

Water pollution is a global environmental challenge of the 21st century. To address this issue, advanced treatment technologies have emerged, among which nanotechnology plays a central role. Recent studies have highlighted the potential of nano-oxides and photocatalysts such as titanium dioxide (TiO,) and zine axide (ZnO) in removing heavy metals, organic pollutants, and pathogenic microorganisms with high efficiency (De Silva ot al., 2025; Tripathy et al, 2024). Solar disinfection has also been recognized as a simple and effective method, yet its efficiency is limited under conditions of high contamination or weak solar radiation (El-Seesy et al., 2016). The integration of photocatalytic nanoparticles with solar energy has therefore been developed as a sustainable and low-cost strategy for water purification, combining strong antimicrobial properties with environmental safety (Wang & Zhang, 2023) To overcome these limitations, the performance of this technology has been improved using photocatalytic nanoparticles, due to their unique optical and chemical properties (Dufner et al., 2025). These materials are used as UV absorbers and have been extensively studied for the removal of organic compounds from polluted air and water, and for microbial disinfection (Adams et al., 2006).

Objectives of the Study:

1.This study is a laboratory experimental study aimed at evaluating the effect of nanomaterials (TiO_2) and (ZnO) on the efficiency of removing pathogenic bacteria from contaminated water using reactors coated with these materials.

2. Measure biological, chemical, and physical variables of water before and after treatment with nanomaterials, such as the total bacterial count, bacterial isolates, and identification.

3. Avoid adding harmful chemicals such as carcinogenic chlorine and costly ozone, and replace them with a safe and sustainable method for water sterilization based on ultraviolet radiation.

Study Area

This study focuses on the city of Mosul, located in northern Iraq between longitudes (41°–44°) east and latitudes (35°–37°) north, straddling the Tigris River, which divides it into a right and left side. The study included a main outlet that flows into the Tigris River:

Al-Maidan Outfall: One of the most important outlets in the old area on the right side, it is designated for draining rainwater and sewage. It begins from Ras Al-Jada, passes through Khazraj, then the Sa'a and Sarj Khana areas, the Sha'areen Market, and the Fish Market. It ends below the old bridge, approximately 1.7 km long (Nineveh Sewerage Directorate), as shown in Figure (1).

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Figure (1) shows the study area

Materials and Methods

Reactor Preparation

Reactors (1L) were coated with 99% pure TiO_2 and ZnO nanoparticles (10-30 nm; Sky Spring, USA), ensuring high surface area and chemical reactivity. Silane coupling agents were applied to stabilize the nanoparticles and prevent agglomeration. After drying for 48 h, the reactors were ready for water treatment experiments under direct solar irradiation. Safe-to-use transparent dyes were supplied by the Turkish company ONAY BOYA. To coat the reactors, the nanomaterials were mixed with a transparent dye to ensure effective adhesion to the reactor surface. The coated reactors were left for 48 hours to ensure the coating was completely dry and prevent it from mixing with water during the treatment phase. After the drying period, water samples were collected from the Meydan and Karasaray estuaries, filtered using medical gauze, and placed in the nanomaterial-coated reactors. Then the samples were left inside the reactors for 3 hours under direct sunlight at noon and temperatures during the study period ranged between (10-35) °C, with an average of about (12.8) °C. The intensity of solar radiation during the study period reached between (700-950 W/m2), as shown in Figure (2).

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Figure (2) shows the reactors under sunlight.

Results and discussion

Biological Properties

1-Total Bacteria Count (TBC) Half an Hour After Treatment

The results showed a significant decrease in the total bacterial count (TBC) after half an hour of treatment with TiO_2 and ZnO nanoparticles compared to the control group. However, this decrease was not as high as that achieved after three hours, indicating that treatment time is a key factor in increasing the efficiency of biological removal (10).

At the Qara Saray outfall

the control group recorded more than 300 cells/ml, reflecting the persistence of biological contamination in the absence of treatment. When ZnO was used at a concentration of 10 mg/ml, the count decreased to 289 cells/ml, but it remained relatively high, indicating that half an hour is not sufficient to achieve effective removal. When the concentration of ZnO was increased to 15 mg/ml, the count decreased to 210 cells/ml, demonstrating the role of the material concentration and treatment time in enhancing efficiency.

In contrast, TiO_2 demonstrated clearer effectiveness, reaching 236 cells/ml at 10 mg/ml and decreasing significantly to 86 cells/ml at 15 mg/ml, reflecting its high efficiency even over short periods. Recent studies have confirmed that TiO_2 has a higher capacity to generate free radicals than ZnO, giving it superiority in inhibiting bacterial growth (11).

At Al-Midan Outfall

At this site, the control group showed high bacterial counts exceeding 300 cells/ml, indicating severe contamination. When TiO_2 and ZnO were used at a concentration

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of 10 mg/ml, a gradual decrease in counts was observed compared to the control, but the values remained relatively high. At the higher concentration of 15 mg/ml, a more pronounced effect was observed, with the number dropping to 82 cells/ml using TiO_2 , while at the same concentration, ZnO recorded 95 cells/ml, reflecting TiO_2 's superiority in eliminating bacteria in just half an hour. These results are consistent with what (12) reported regarding TiO_2 's greater efficiency in treating microbial contaminants compared to ZnO under the same operating conditions.

Scientific Interpretation of the Results

These results can be explained by TiO_2 's ability to produce free radicals (•OH) more rapidly when exposed to radiation, leading to rapid damage to bacterial cell walls and membranes even in a short time (13). However, half an hour is still not sufficient to completely eliminate bacteria, as significant numbers continued to appear, unlike after three hours, when a much greater reduction was achieved (14). The differences between the Kara Saray and Midan estuaries may be attributed to the nature of the pollution. Kara Saray contains more complex industrial pollutants that may hinder the efficiency of catalytic reactions, while Midan is predominantly composed of biodegradable organic pollution, which facilitates the nanoremediation process and enhances its effectiveness (14). Thus, it can be concluded that the half-hour results demonstrate the initial effectiveness of the nanoparticles, especially TiO_2 , and that increasing the treatment time is necessary to enhance the effect and achieve near-complete elimination of bacteria.

Table (1): Total number of bacteria after half an hour of treatment

Sample Location	Concentration(mg/ml)	TiO2	ZnO
Qara Saray outfall	Control	more 300	more 300
	10	236	289
	15	86	210
Al-Midan outfall	Control	more 300	more 300
	10	175	181
	15	82	95

2-Total Bacteria Count (T.B.C.) One Hour After Treatment

The study results showed a significant decrease in the total bacterial count after one hour of treatment compared to the control group. However, this decrease did not reach the level achieved after three hours, indicating that the treatment duration is a crucial factor in enhancing the bioefficiency of nanomaterials (14).

At the Qara Saray outfall

the results showed that the control group recorded more than 300 cells/ml, reflecting the high level of contamination at the site. As for the TiO_2 treatments, the count decreased at a concentration of 10 mg/ml to 45 cells/ml, while the higher concentration (15 mg/ml) showed more pronounced efficiency, with the count decreasing to 18

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cells/ml. In contrast, the number of bacterial cells in the 10 mg/ml ZnO reactor reached approximately 58 cells/ml, while at 15 mg/ml, it decreased to 38 cells/ml.

It is noted that TiO_2 significantly outperformed ZnO in reducing the total bacterial count at both concentrations at this site, which is consistent with previous studies indicating that TiO_2 possesses higher photosynthetic activity due to its chemical stability and ability to generate reactive oxygen species more effectively (15).

At the Al-Midan outfall

the control group recorded more than 300 cells/ml, reflecting the high level of pollution similar to the Kara Saray outfall. In the nanoreactors, the number reached 6 cells/ml at 10 mg/ml TiO_2 and 9 cells/ml at the same concentration ZnO. At the highest concentration (15 mg/ml), both TiO_2 and ZnO recorded the lowest possible number of 2 cells/ml.

These results indicate a very high efficacy of the nanoparticles at the Meydan site, especially at the highest concentration (15 mg/ml), where bacterial counts reached their lowest level. These results are consistent with recent scientific reports demonstrating that increasing the concentration of nanomaterials leads to enhanced free radical generation, thereby increasing the efficiency of bacterial elimination (12).

The T.B.C. results can be explained by the fact that the efficacy of the nanomaterials is evident even after one hour of treatment, but their effect becomes more pronounced after longer periods. The discrepancy between the two estuaries is due to the different nature and types of pollutants. The Kara Saray estuary contains more complex industrial wastes that may hinder some photocatalytic reactions, while the Meydan estuary is predominantly characterized by biodegradable organic pollutants, which enhances photocatalytic efficiency (11).

The results of Table (2) confirm that treatment using TiO_2 outperformed ZnO, which is in line with recent research trends that consider TiO_2 to be one of the most promising nanomaterials in the field of photochemical treatment of polluted water (13).

Scientific Interpretation of the Results

3- Total Bacteria Count (TBC) Three Hours After Treatment

The results showed a significant decrease in the total bacterial count (TBC) three hours after treatment with nanoparticles, compared to the control group, which recorded high counts at both sites. This confirms the effectiveness of the treatment time in enhancing the effectiveness of nanoparticles (16).

At the Qara Saray outfall

the results indicated that ZnO at a concentration of 15 mg/ml reduced the bacterial count to 6 cells/ml, while TiO_2 at the same concentration showed greater effectiveness, reducing the count to only 3 cells/ml. The control group, on the other hand, exceeded 300 cells/ml, reflecting the persistence of biocontamination in the absence of any treatment. This superiority is attributed to the optical and physical properties of TiO_2 , which give it a higher capacity to produce reactive oxygen species (ROS),

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thus achieving greater disinfection efficiency (17).

Table (2): Total number of bacteria after one hour of treatment

Sample Location	Concentration(mg/ml)	TiO2	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

At the Al-Midan outfall

the number reached zero cells/ml when TiO_2 was used at a concentration of 15 mg/ml, demonstrating very high effectiveness in eliminating bacteria. ZnO at the same concentration reduced the number to 2 cells/ml, a significant decrease compared to the control reactor, which recorded over 180 cells/ml. These results indicate that TiO_2 outperforms ZnO under natural lighting conditions due to its higher photocatalytic activity compared to ZnO (18). The sharp decrease in T.B.C after three hours can be explained by the following:

The high efficiency of nanoparticles, especially TiO_2, in catalyzing photochemical reactions that produce free radicals (•OH) capable of directly damaging bacterial cell walls and membranes.

The greater efficiency of TiO_2 compared to ZnO is due to its stronger photonic properties under natural irradiation, in addition to its chemical stability, which enhances the continuation of reactions for longer periods (19).

The difference between the two sites may be attributed to the nature and source of the pollution; the type, quantity, and concentration of pollutants directly affect the efficiency of the nanoremediation process (20).

The results of Table (3) show: how that treatment with TiO_2 and ZnO contributed to a significant reduction in bacterial counts after three hours, confirming the potential of these nanomaterials as a promising method for treating biological pollution in water. The study also showed that TiO_2 showed clear superiority over ZnO, which is consistent with recent trends in research related to nanophotonic processing (21).

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Table (3): Total number of bacteria after three hours of treatment

Sample Location	Concentration(mg/ml)	TiO2	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

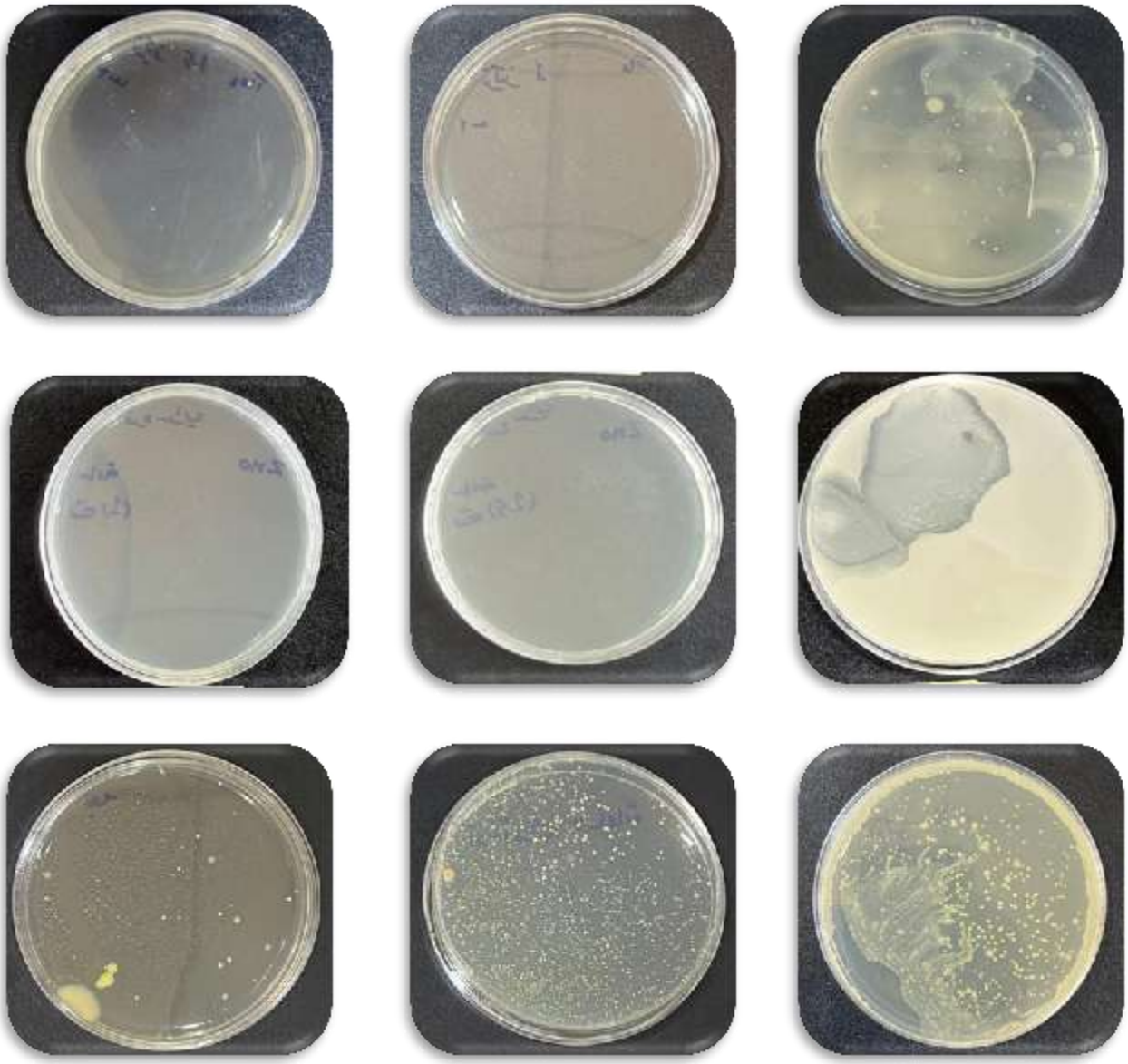

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Figure (3) Illustrative images of biological treatment

Chemical properties

Total Hardness (T.H)

The results indicate that the total hardness concentration remained stable at 170 mg/L in all samples, both in the control reactors and the nanoparticle reactors at concentrations of 10 and 15 mg/mL and for different exposure times (half an hour, one hour, and three hours). This stability indicates that the nanomaterials used did not cause a change in the concentrations of calcium and magnesium ions, the two main components of total hardness (22). This is due to the photocatalytic mechanism these particles rely on, as they focus primarily on the oxidation of organic compounds such as nitrate, phosphate, and sulfate, and do not interact directly with the ions responsible for hardness (23). Previous studies have shown that the effect of nanoparticles on total hardness is limited, especially when chemical and physical conditions such as temperature and pH are constant, and when precipitating agents are not available (24). On the other hand, nanomaterials are not as efficient in removing hardness compared to traditional methods such as ion exchange (25). These results are consistent with recent research, which indicated that the stability of the concentration of Ca^{2+} and Mg^{2+} ions during the experiment is due to the stability of the water temperature and pH, which are key factors in the precipitation or dissolution of these ions (26).

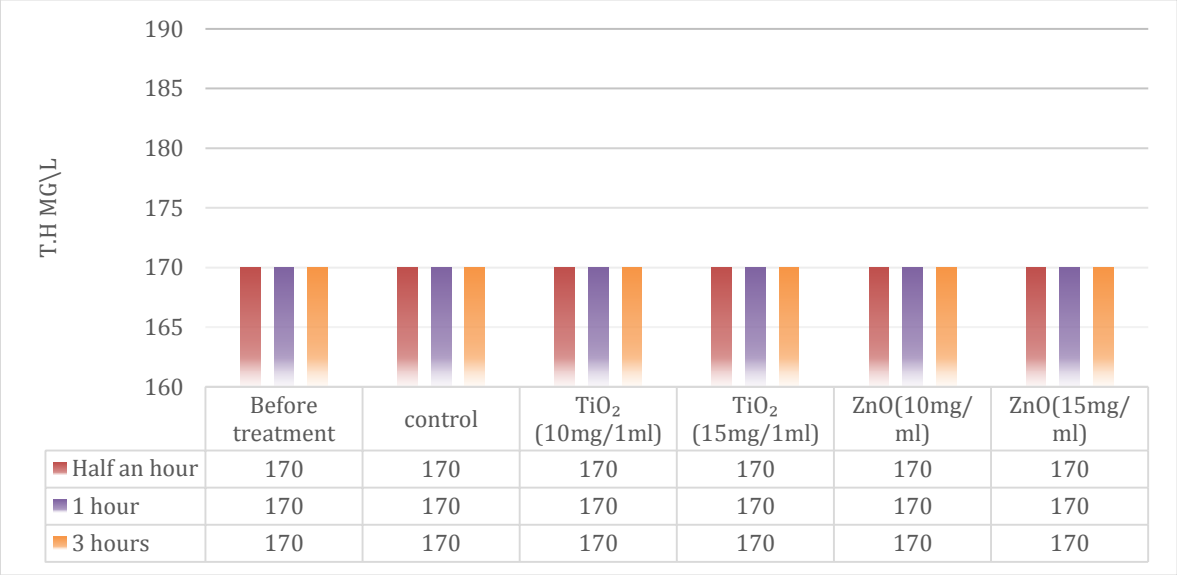

Figure (1) Total hardness concentrations in terms of $CaCO_3$ (mg/L)

Calcium Hardness (Ca H.)

The results indicated that the calcium hardness concentration remained stable at 40 mg/L in all reactors. This stability is due to the fact that the nanoparticles did not affect the concentration of calcium ions (Ca^{2+}), which are the main component of calcium hardness (22). This is attributed to the fact that the photocatalytic mechanism on which

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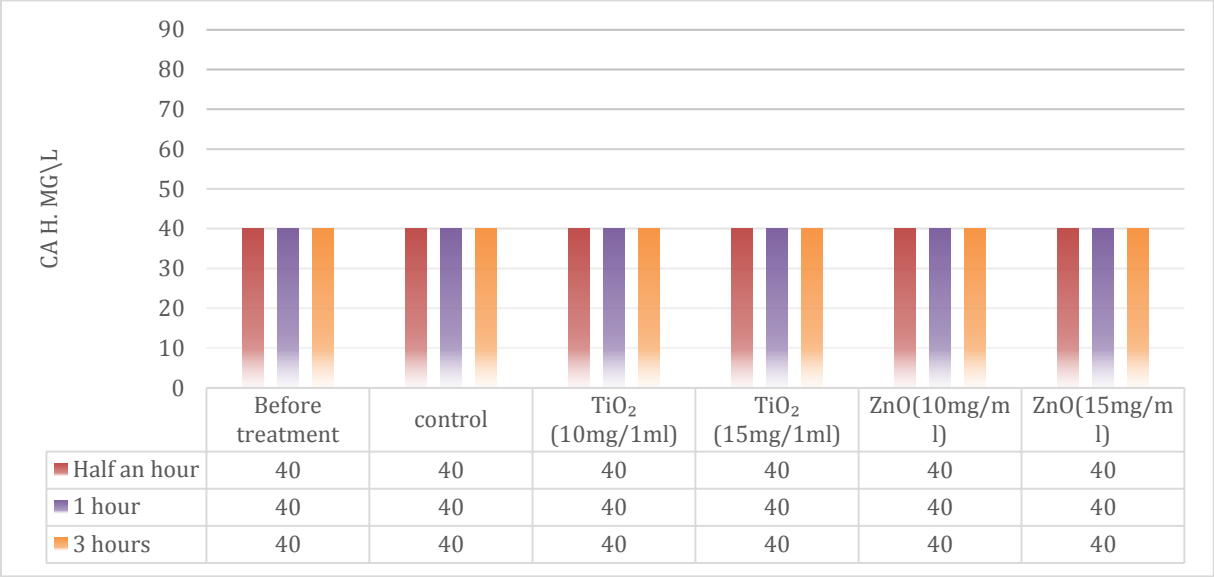
these nanoparticles rely focuses on the oxidation of organic compounds while not directly interacting with stable inorganic ions (23).



	Before treatment	control	TiO_2 (10mg/1ml)	TiO_2 (15mg/1ml)	ZnO(10mg/ml)	ZnO(15mg/ml)
Half an hour	40	40	40	40	40	40
1 hour	40	40	40	40	40	40
3 hours	40	40	40	40	40	40

Figure (2) Calcium hardness concentrations as a function of $CaCO_3$ (mg/L)

Magnesium Hardness (Mg H.)

The results confirmed that the magnesium hardness concentration also remained constant at 130 mg/L in all reactors. Mg^{2+} ions are chemically stable and do not readily undergo oxidation or reduction reactions, making them unaffected by photocatalytic techniques (24). Furthermore, the nanomaterials used lack the ion exchange properties required to remove magnesium ions from water (27). Studies indicate that removing Mg^{2+} ions requires different techniques such as ion exchange and reverse osmosis (RO), which rely on physical mechanisms (25; 26).

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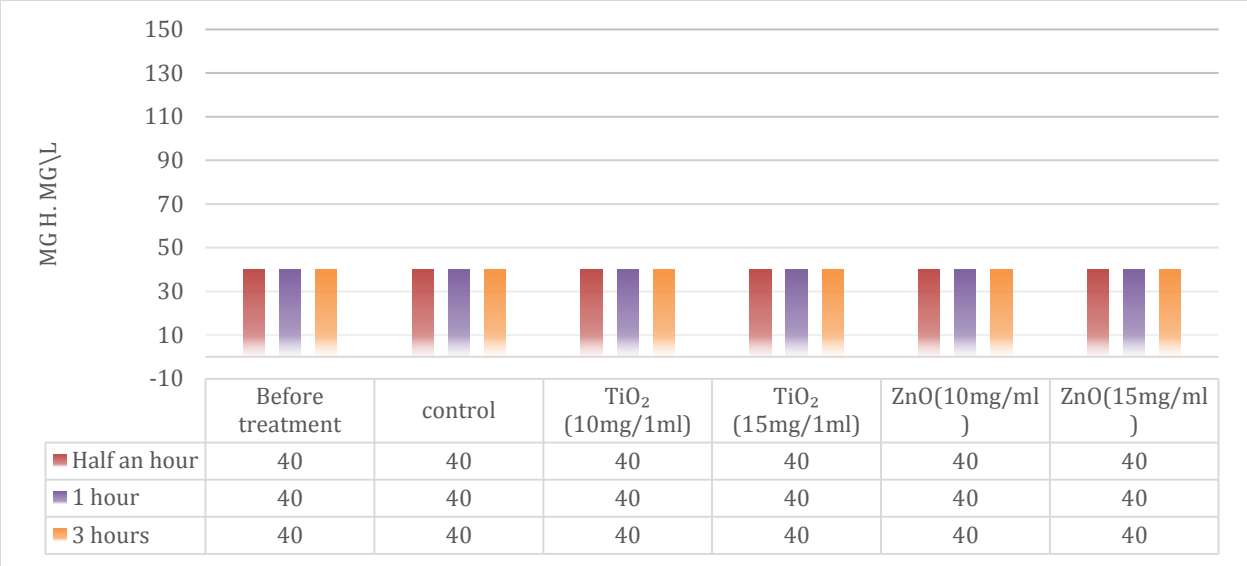

Figure (3) Magnesium hardness concentrations in terms of $CaCO_3$ (mg/L)

Chloride Ion (Cl^-)

The results of the current study showed that the chloride ion (Cl^-) concentration remained stable at 74 mg/L in all reactors, both the control reactors and the nanoparticle reactors. This stability indicates that the nanomaterials did not cause any changes in chloride concentration. This behavior is attributed to the fact that the photocatalytic mechanism used by TiO_2 and ZnO primarily targets the photodegradation of organic compounds, but does not participate in reactions that affect stable ions (22). In addition, the chloride ion is chemically stable in solution and is not easily susceptible to oxidation and reduction, making it unlikely to be affected within the experimental time range and exposure levels used. (28) There are indications that Cl^- sometimes slows the activity of the free radical •OH by altering the reaction mechanism, but it is not itself affected.

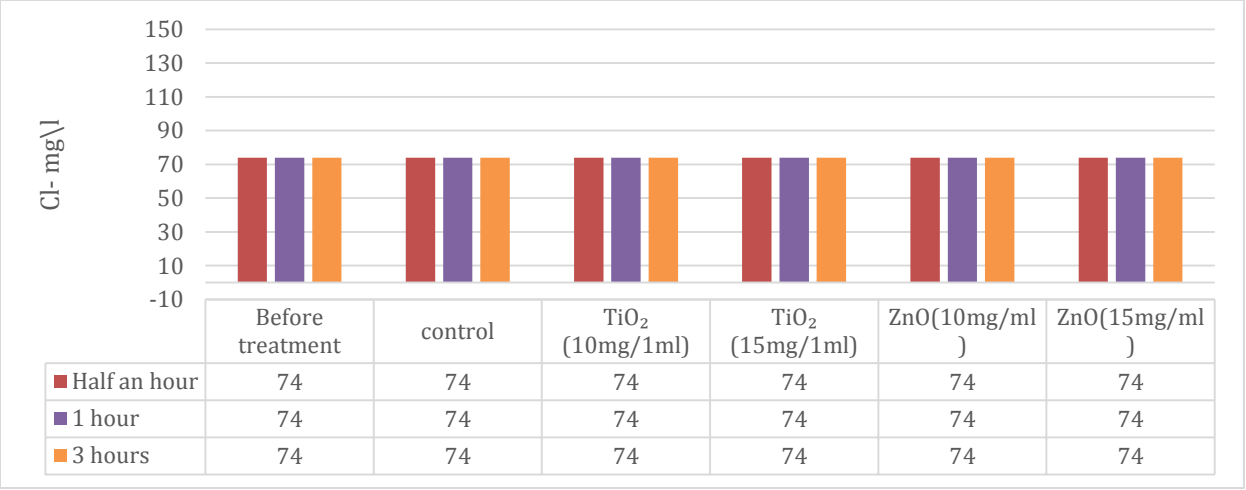

Figure (4) Chloride ion concentrations (mg/L)

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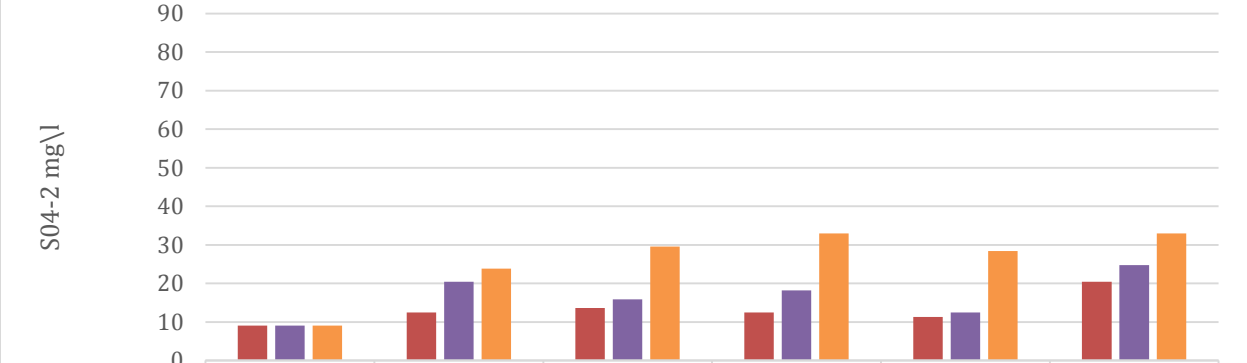
) SO_4^{-2} (Sulphate Ions

The results showed that the sulfate concentration (before treatment) remained constant at 0.9 mg/L for all exposure periods (half an hour, one hour, and three hours), confirming the stability of sulfate concentrations in the absence of nanomaterials. After applying treatment using nanoparticles at two different concentrations (10 and 15 mg/L), a clear variation in sulfate concentrations was recorded with time and concentration, reflecting the effectiveness of these materials in influencing the behavior of sulfate in water. When TiO_2 was used at a concentration of (10 mg/L), the sulfate concentration gradually increased with time, reaching values of (13.63, 15.90, and 29.54 mg/L) for half an hour, one hour, and three hours, respectively. Similarly, samples treated with TiO_2 at a concentration of (15 mg/L) showed greater increases, reaching values of (12.50, 18.18, and 32.95 mg/L). This increase can be explained by the increased decomposition of sulfur-containing compounds (such as organic sulfates) under the influence of TiO_2 nanoparticles, resulting from the formation of reactive oxygen species (ROS) during the photocatalytic process (29). Treatment with ZnO at a concentration of 10 mg/mL showed relatively smaller incremental increases (11.36, 12.50, and 28.40 mg/L), while ZnO at a concentration of 15 mg/mL recorded the highest increases (20.45, 24.77, and 32.95 mg/L). The superior performance of ZnO at high concentrations is attributed to its ability to catalyze organic sulfate oxidation reactions more rapidly, in addition to the photocorrosion phenomenon that increases sulfate release (30, 31). These results are consistent with the findings of several previous studies, which confirmed that nanoparticles are highly effective in stimulating the oxidation and decomposition of organic and sulfur compounds in water (32,33). Some studies have also indicated that increasing the concentration of nanoparticles and increasing the exposure time leads to increased sulfate production as a result of the oxidation of organic sulfur (34).



	Before treatment	control	TiO_2 (10mg/1ml)	TiO_2 (15mg/1ml)	ZnO(10mg/ml)	ZnO(15mg/ml)
Half an hour	9.09	12.5	13.63	12.5	11.36	20.45
1 hour	9.09	20.45	15.9	18.18	12.5	24.77
3 hours	9.09	23.86	29.54	32.95	28.4	32.95

Figure (5) Concentrations of sulfates and nitrates (mg/L)

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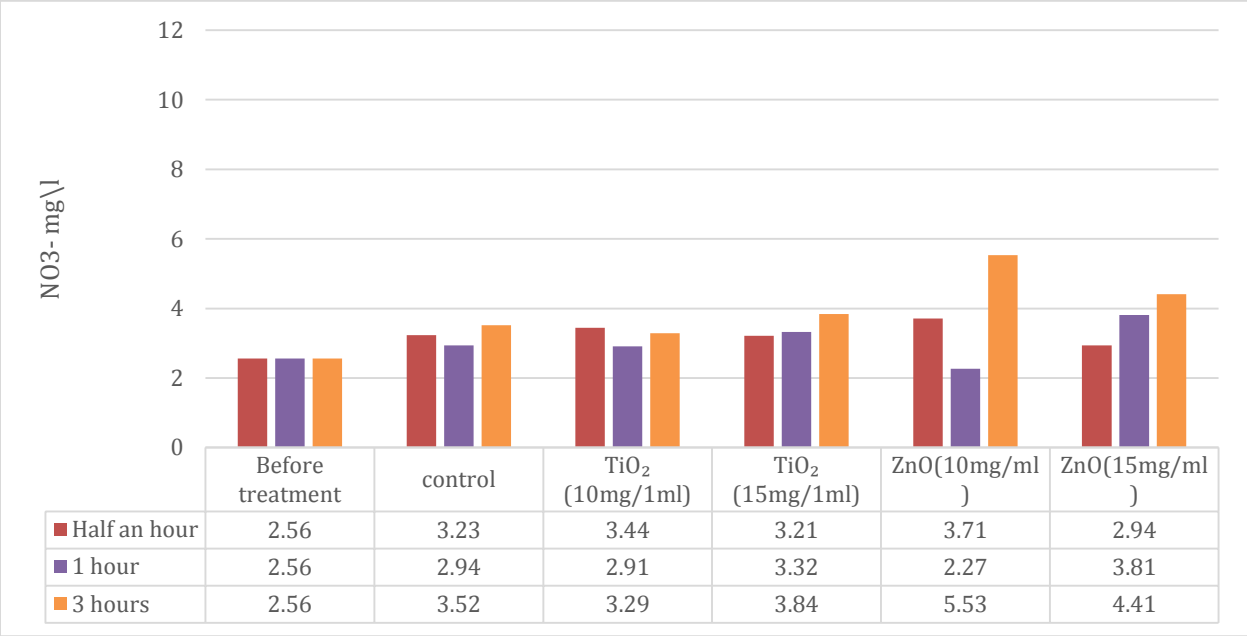
) NO_3^- (Nitrate Ions

The results showed that the nitrate concentration before treatment remained constant at 2.56 mg/L for all exposure times (half an hour, one hour, and three hours), reflecting the stability of nitrate concentrations in the absence of nanomaterials. However, in samples treated with nanoparticles, a significant change in nitrate concentrations was observed depending on the type and concentration of the nanomaterial and exposure time. When using TiO_2 at a concentration of 10 mg/ml, the nitrate concentration gradually decreased from 3.44 mg/L after half an hour to 2.91 mg/L after one hour, then increased again to 3.29 mg/L after three hours. When using TiO_2 at a concentration of 15 mg/ml, values of 3.2, 3.32, and 3.84 mg/L were recorded for the same treatment times. These increases indicate that TiO_2 particles can contribute to the oxidation of nitrogenous compounds (ammonium and nitrite) to nitrate due to the presence of reactive oxygen species (ROS) under photocatalysis (35; 10). For samples treated with ZnO at a concentration of 10 mg/mL, a different pattern was recorded, with values ranging from 3.71, 2.27, and 5.53 mg/L, reflecting oscillatory behavior due to the photoelectric effect and the instability of ZnO in water, which can cause temporary release or absorption of nitrate (36). For ZnO at a concentration of 15 mg/ml, values of 2.94, 3.81, and 4.4 mg/L were recorded, which also showed a gradual increase in nitrate concentration with increasing time and concentration, supporting the hypothesis that ZnO is more active than TiO_2 in catalyzing the oxidation of nitrogenous compounds (37). These results are consistent with recent studies that confirmed the ability of TiO_2 and ZnO to oxidize and convert nitrogenous compounds to nitrate, with differences in the degree of stability and performance between the two materials (38).

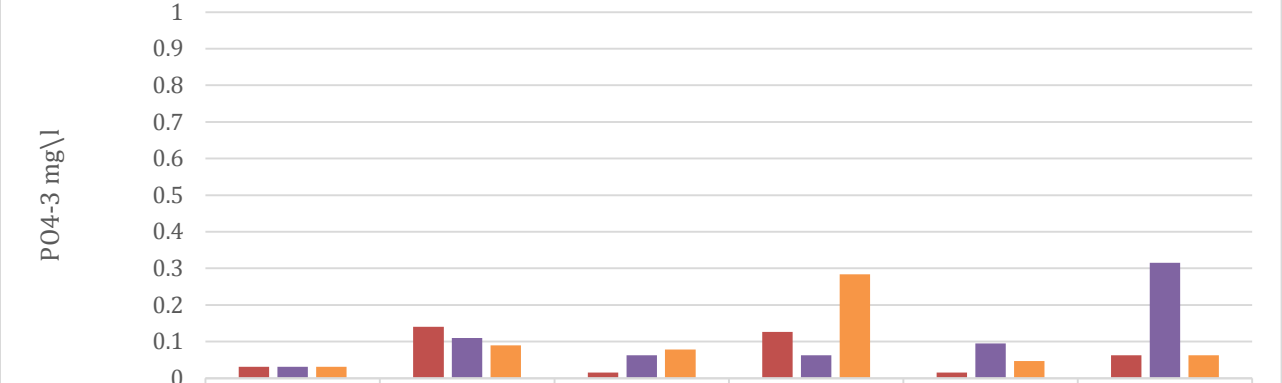


	Before treatment	control	TiO_2 (10mg/1ml)	TiO_2 (15mg/1ml)	ZnO(10mg/ml)	ZnO(15mg/ml)
Half an hour	2.56	3.23	3.44	3.21	3.71	2.94
1 hour	2.56	2.94	2.91	3.32	2.27	3.81
3 hours	2.56	3.52	3.29	3.84	5.53	4.41

Figure (6) Nitrate ion concentrations (mg/L)

) PO_4^{-3} (Orthophosphate Ions

The results indicate that the phosphorus concentration before treatment was stable at 0.031 mg/L, while the comparison results after half an hour of treatment showed a significant increase, reaching 0.14, and then began to gradually decrease after one and three hours of treatment, reaching 0.11 and 0.09, respectively. Samples treated with nanoparticles recorded varying decreases in phosphorus concentration depending on the type of nanomaterial, its concentration, and exposure time. When using TiO_2 at a concentration of 10 mg/ml, a gradual decrease in phosphorus concentration was observed, reaching 0.015 mg/L after half an hour, 0.063 mg/L after one hour, and 0.078 mg/L after three hours. Samples treated with TiO_2 at a concentration of 15 mg/ml showed a significant improvement in removal efficiency, as the phosphorus concentration decreased from 0.126 mg/L after half an hour to 0.063 mg/L after an hour, and then increased again to 0.284 mg/L after three hours, reflecting the role of the increased nanomaterial concentration in enhancing the adsorption and photocatalytic activity of phosphorus (39). When using ZnO at a concentration of 10 mg/ml, values of 0.015, 0.095, and 0.047 mg/L were recorded for the same exposure times, with relatively fluctuating performance. While samples treated with 15 mg/ml ZnO showed a significant variation in values, recording (0.063 mg/L) after half an hour, unexpectedly rising to (0.315 mg/L) after an hour, and then decreasing again to (0.063 mg/L) after three hours. This unstable behavior is attributed to the phenomenon of photolysis and the decomposition of ZnO particles under radiation, which leads to a temporary release of absorbed phosphorus (31; 40). All results of the current study were within and below the permissible limit for discharge into rivers, which is (3) mg/L. The results of the current study differed from the results of the study (41) during his study to assess the environmental impact of some liquid discharges into the Tigris River, as his highest concentration reached (25.9) mg/L.



	Before treatment	control	TiO_2 (10mg/1ml)	TiO_2 (15mg/1ml)	ZnO(10mg/ml)	ZnO(15mg/ml)
Half an hour	0.031	0.14	0.015	0.126	0.015	0.063
1 hour	0.031	0.11	0.063	0.063	0.095	0.315
3 hours	0.031	0.09	0.078	0.284	0.047	0.063

Figure (7) Concentrations of orthophosphate ions (mg/L)

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Conclusions

1. Reactors coated with nanomaterials improved treatment efficiency. The study demonstrated that nanomaterials (TiO_2 and ZnO) are effective in reducing the number of bacteria contaminating water. The total bacterial count (T.B.C.) decreased significantly to 0 cells/ml in treated samples, demonstrating the effectiveness of this technology in water disinfection.

2. Titanium oxide (TiO_2) demonstrated higher efficiency than zinc oxide (ZnO) in removing bacteria, making it the most effective choice for practical applications.

3. The effect of nanomaterials on bacterial contaminants was more pronounced compared to chemical properties. ions (chloride, sulfate, nitrate, phosphorus) and total hardness showed relative stability, with minor changes that did not affect water quality.

4. Biological treatment using nanomaterial-coated reactors powered by solar energy is a promising option for highly efficient treatment of contaminated water.

5. Therefore, solar-powered reactors coated with nano-oxides represent a practical, low-cost. and sustainable solution for decentralized water treatment. This approach holds particular promise for rural and polluted regions, where access to safe drinking water remains a critical challenge.

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