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Sustainable Lake Water Treatment Using Titanium Dioxide Nanowires Technology

Tan Sze Chi, Evyan Yang Chia Yan*, Le Hoang My, Jie Vincent, Chia Chin Hua and Zhao Jinhui

***Abstract* – Water is essential for the entire organism to survive and maintaining ecosystem. There are still limitations of the conventional water treatment including high building and maintenance cost, high energy consumption, limited removal of emerging contaminants and other complications that required compliance from different parties. The application of photocatalytic oxidation has attracted a great deal of attentions upon its ability to overcome the limitations. Titanium dioxide (TiO_2) is one of the photocatalysts which possess high efficiency in removing the environmental contaminants. Modification of dimension of nanoparticles enhance the properties and improve their application. In this study, it is aimed to synthesize one-dimensional (1-D) nanostructural TiO_2 nanowires via one step hydrothermal process followed by post-heat treatment. With 1-D TiO_2, the photocatalytic performance and antimicrobial activity of TiO_2 were improved. In present study, the lake water cultures and *Escherichia coli* (*E. coli*) were used as the model organisms on the antimicrobial property of TiO_2 nanowires for the application in lake water treatment. Based on the results, ultraviolet-visible (UV-vis) spectrum revealed post-heat treatment enhanced the crystallinity and the light absorption ability of TiO_2 nanowires. The calcined TiO_2 nanowires displayed higher efficiency in controlling the micropollutants of lake water. The antimicrobial results revealed that the addition of TiO_2 nanowires into the lake water and *E. coli* samples enhanced the anti-bacterial activity by showing the highest removal efficiency (up to 99.9%) as compared to samples with TiO_2 nanoparticles and plain samples under UV irradiation alone. Hence, the results suggested that photocatalytic TiO_2 nanowires can be effectively applied in the treatment of agricultural and industrial wastewater, contributing to sustainable future with achievement of SDG 6 (Clean Water and Sanitation) and SDG 3 (Good Health and Well-Being).**

Keywords—Aquaculture, Nanowires, Photocatalytic, Post-Heat Treatment, Antibacterial Activity, UV Irradiation.

I. INTRODUCTION

Water is essential for the entire organism to survive. Lake plays an important role in storing water for usages to the community in terms of agriculture, aquaculture, drinking water and etc. In addition, lake water also helps in maintaining ecosystem [1]. The

*Corresponding Author email: evyanyang@nilai.edu.my, ORCID: 0000-0003-0619-1103

Tan Sze Chi, Faculty of Intelligent Healthcare Technology, Nilai University, Nilai, Negeri Sembilan, Malaysia. (e-mail: tschii99@gmail.com)

Evyan Yang Chia Yan, Department of Research and Innovation, Nilai University, Nilai, Negeri Sembilan, Malaysia. (e-mail: evyanyang@nilai.edu.my)

Le Hoang My, Department of Research and Innovation, Nilai University, Nilai, Negeri Sembilan, Malaysia. (e-mail: lehmy108@gmail.com)

Jie Vincent, Department of Applied Physics, Faculty of Science and Technology, National University Malaysia, Selangor, Malaysia. (e-mail: p140672@siswa.ukm.edu.my)

Chia Chin Hua, Department of Applied Physics, Faculty of Science and Technology, National University Malaysia, Selangor, Malaysia. (e-mail: chia@ukm.edu.my)

Zhao Jinhui, Faculty of Modern Agriculture and Environment, Weifang Institution of Technology, Shandong, China. (e-mail: 364002971@qq.com)

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enormous amount of organic and inorganic pollutants has been discharging into the rivers every day, causing pathogenic microbial contamination in water [2]. This unavoidably leads to many consequences like health and environmental issues. Although high cost has spent in treating polluted water, the conventional water treatment process, it cannot fully meet the standards of safe water quality [3], [4].

Access to clean and safe water is a global challenge aligned with SDG 6 (Clean Water and Sanitation), while improved water treatment supports SDG 3 (Good Health and Well-Being) by reducing waterborne diseases. Therefore, researchers all over the world have made much effort on testing various approaches in order to improve the efficiency of water purification and solid waste management systems, including the application of novel adsorbent and catalytic materials and automated waste classification for improved source control [5] [6]. As the importance of integrating material-based treatment technologies with intelligent environmental management systems becomes more recognised, alongside automated waste classification help reduce solid waste leakage into rivers and lakes, photocatalytic nanomaterials target microbial contamination in water.

The application of photocatalytic oxidation of nano semiconductor such as TiO_2, ZnO, CuO have become a great interest over the decades. The particle size of nanoparticles approximately less than 100 nm in diameter has been proven to be the most efficient alternative for water purification treatment. They are used extensively for the removal of micropollutants in water treatment due to its interesting properties such as non-toxicity, cost-effective, highly efficient, biologically and chemically inert, photo-induced super-hydrophobicity as well as it is sustainable [7], [4].

Titanium dioxide (TiO_2) has been widely recognized as an effective photocatalyst capable of decomposing or inactivating a broad range of micropollutants in water, including humic substances, bacteria, viruses, algal toxins, and fungi. It has also been shown to break down hazardous organic compounds such as paints, pesticides, and deodorants into harmless byproducts that enable it to be used in wastewater treatment in industries [8], [9].

However, the surface area of TiO_2 tends to decrease with increased calcination time and heating rate due to the collapse of its pores, which occurs during the transformation from amorphous TiO_2 to the anatase phase. Additionally, separating TiO_2 nanoparticles from treated water is energy-intensive and costly [10]. To address these limitations, researchers have developed one-dimensional (1D) TiO_2 nanowires [11]. Compared to conventional TiO_2 powder, these nanowires exhibit higher crystallinity and larger surface area, which enhance their photocatalytic performance. Notably, they also demonstrate improved hydrogen evolution efficiency and greater thermal stability at elevated temperatures. From a system-level perspective, it is important to integrate photocatalytic water treatment with clean, sustainable energy sources. Hybrid renewable energy systems have been reported to improve environmental technologies efficiency and resilience using intelligent system design and optimization [12]. By such combination, the TiO_2 nanowire system can run more efficiently and for longer periods of time, especially helpful for continuous operation or large-scale water treatment, where stability and long-term use are important.

In this study, TiO_2 nanowires will be synthesized for the application of lake water treatment. The synthesis method is optimized the photocatalytic performance and improve antimicrobial activity of TiO_2 nanowires by modifying its surface area. With this optimization, the TiO_2 nanowires aim to have high potential to utilize its application in the industrials especially in the treatment of wastewater at better performance.

II. METHODOLOGY

In this experiment, TiO_2 nanowires were synthesized via hydrothermal method which was modified from Evyan et al., 2014 [13]. The desired amount of titanium dioxide powder (Sigma-Aldrich) was dispersed in 10 M NaOH (R & M Chemicals) alkaline aqueous solution followed by stirring process using magnetic stirrer for 45 minutes. Subsequently, the mixture was poured into a 50 ml Teflon-lined stainless autoclave and heated at 180°C for 8 hours. The precipitates were collected via centrifugation and washed thoroughly with 1 M HCl solution (R & M Chemicals) and distilled water alternatively until the pH level approached approximately 7.0. The obtained precipitates were dried in the oven at 60°C and further calcinated in programmable furnace at 500°C for 2 hours.

Nutrient agars (NA) plates were prepared by mixing of nutrient agar (Merck, Germany) and distilled water in the Scott bottles. NA bottles were autoclaved at 121°C for 30 minutes and poured immediately into plates for solidification. Besides that, Nutrient broth (NB) (Merck, Germany) mediums were prepared by nutrient broth and distilled water in the Scott bottle. It was autoclaved and cooled in the room temperature. The lake water samples were collected from the lake in Nilai University and brought to the laboratory for analysis within the same hour. Preliminary analysis was carried out via spread plate method to examine and confirm the presence of microorganisms in the water samples.

Escherichia coli (*E. coli*) bacteria was chosen as the representative organisms of water coliforms as it often found in feces contaminating water [14], [15]. The *E. coli* colony that are picked from a culture plate were inoculated into NB broth by using a sterile inoculating loop. The sample was left in the shaker overnight for facilitating bacteria growth. The samples consisted lake water (control); lake water treated with only UV; lake water treated with TiO_2 nanowires. On another hand, the samples consisted *E. coli* suspension (control); *E. coli* suspension treated with TiO_2 nanowire, and *E. coli* suspension treated with TiO_2 nanoparticles. Notably, both lake water and the *E. coli* suspension without being treated with TiO_2 were acted as a control in the experiment. All the samples were put under the UV exposure for 24 hours and centrifuged. After the centrifugation, the supernatants were collected, and followed by spread-plating. For *E. coli* samples, they were serial diluted to the concentration of 10-4 before spread-plating. The concentration was chosen based on the previous study [16]. The suspensions from the lake water samples and *E. coli* samples with a concentration of 10-4 were micropipetted and spread evenly on the surface of NA plates respectively. All the agar plates were inverted and incubated at 37 °C for 24 hours, and the numbers of bacterial colonies were observed.

Three replicates were carried out for each sample. The results were collected from the samples at 2 hours, 3 hours, 4 hours and 24 hours of UV irradiation respectively to observe the effect of irradiation time on the microbial cells removal. After all, the colonies growth on the plates were counted and plotted into graphs and charts. Moreover, the growth inhibition rates of each sample were determined by using the formula as given in (1) [16]. All the results were analyzed and reported as mean ± standard deviation (SD).

$$R\,(\%) = (A - B) / A \qquad (1)$$

Where R is the growth inhibition rates, A is the number of bacterial colonies from control sample, and B is the number of bacterial colonies after treated.

III. Results and Discussion

The physical morphology and the optical absorbance of the samples were observed. Figure 1 demonstrates the physical outlook of TiO_2 commercial powder which as starting material and TiO_2 nanowires which synthesized via hydrothermal method, both of them in powder form and look alike based on their physical appearance. However, there are obvious differences when observed through SEM as shown in Figure 2. The TiO_2 commercial powder has spherical-shapes while TiO_2 nanowires were appeared in long wire-shapes. The change in morphology indicated that the starting material has been converted from zero-dimension spherical form to one-dimensional wires form after hydrothermal process which the starting TiO_2 powder subjected to 10 M NaOH and heated in 180°C for 8 hours. According to Wellia et al. [17], high temperature and strong alkaline solution trigger the formation of solid nanowires.

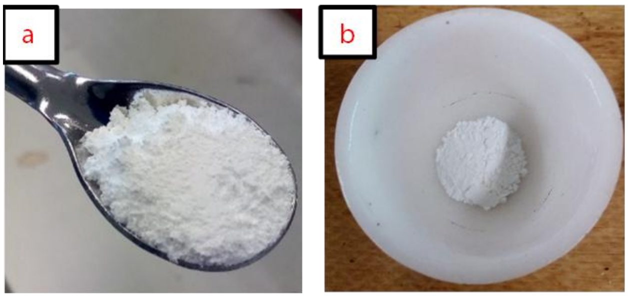

FIGURE 1. (a) TiO_2 commercial powder; (b) TiO_2 nanowires synthesized from hydrothermal.

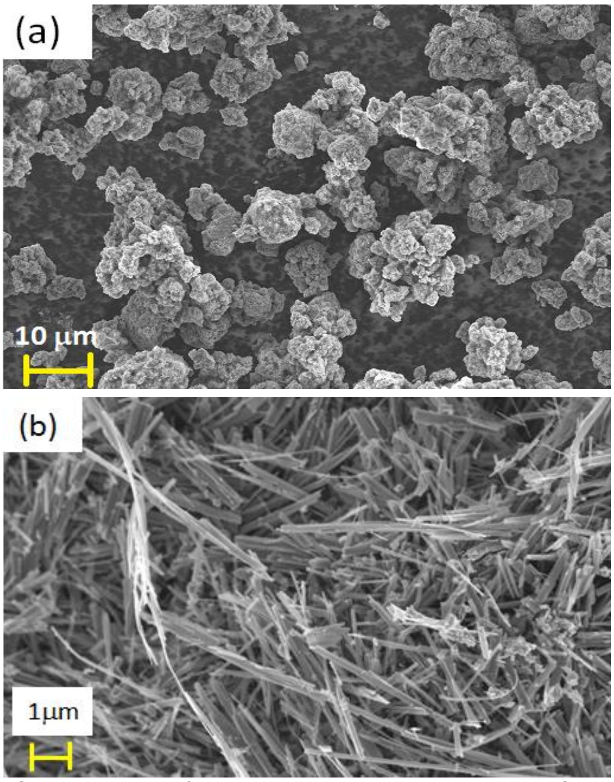

FIGURE 2. Images from scanning electron microscope (SEM): (a) TiO_2 commercial powder; (b) TiO_2 nanowires synthesized from hydrothermal.

The optical absorbance of TiO_2 nanowires was examined by UV-vis spectrophotometer as shown in Figure 3. The spectra of TiO_2 starting material and the synthesized TiO_2 nanowires was almost similar, both obtained a peak at 380 nm meanwhile the synthesized TiO_2 nanowires have higher peak intensities compared to the commercial powder. In addition, the calcined TiO_2 nanowires showed remarkably higher peak intensity compared to the uncalcined nanowires. Post-heat treatment of the synthesized titanium dioxide nanowires was conducted at 500°C for 2 hours based on the optimized condition reported in the previous work by Munisparan et al. [11]. At temperature up to 500°C, it promotes the transformation of poorly ordered TiO_2 into a highly crystalline anatase framework, accompanied by grain growth and removal of residual surface impurities [18]. Such structural refinement facilitates more efficient photogenerated charge transport and suppresses electron–hole recombination, thereby enhancing photocatalytic performance. The increase in crystallinity and the formation of a more stable anatase phase is generally considered the dominant factors governing improved photocatalytic activity [19].

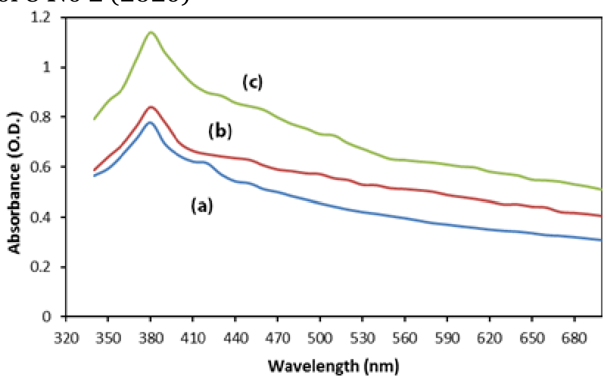

FIGURE 3. UV-vis absorbance spectra of TiO_2 nanowires: (a) TiO_2 powder as the starting material; (b) uncalcined TiO_2 nanowires; and (c) calcined TiO_2 nanowires.

The antibacterial activity of TiO_2 nanowires was evaluated by photocatalytic reaction against lake water cultures and *E. coli* bacteria. In order to rectify whether the UV light affects the survival of the bacterial cells, the antibacterial activity of TiO_2 nanowires was compared with the samples that put under the UV irradiation without the presence of TiO_2 and also compared with the samples with TiO_2 nanoparticles. The resulting numbers of colonies survival in each treating system were plotted into graphs and charts for better comparisons. Figure 4 and Figure 5 demonstrate the antimicrobial effects of various treating systems in affecting the population growth of the lake water samples respectively in the aspect of time for irradiation. From the figures, it has clearly shown that the microbial population was significantly decreased after the samples were treated with only UV, TiO_2 nanoparticles and TiO_2 nanowires as compared to the control sample. The presence of both TiO_2 and UV irradiation would produce hydroxyl radicals (OH) and superoxide, leading to increasing in the efficiency of the photocatalytic process. The bactericidal activity of TiO_2 photocatalysts is primarily associated with the formation of reactive oxygen species, particularly hydroxyl radicals and superoxide anions, which induce oxidative damage on bacterial membranes, increase cell permeability, and disrupt intracellular biomolecules including proteins, RNA, and DNA [20], [21]. The antibacterial activities of TiO_2 are schematized in Figure 6. Recent studies have demonstrated that one-dimensional TiO_2 nanostructures exhibit superior antibacterial efficiency compared with conventional particulate TiO_2 due to their anisotropic electron transport pathways, high interfacial contact area, and enhanced charge separation. For instance, aligned TiO_2 nanotextured arrays were reported to significantly inhibit bacterial adhesion and viability through ROS-mediated surface interactions [22]. Similarly, engineered TiO_2 photocatalytic nanostructures under visible-light irradiation achieved bacterial inactivation efficiencies exceeding 99% by accelerating interfacial oxidative stress and membrane decomposition [23]. Therefore, the presence of one-dimensional TiO_2 nanowire photocatalysts can remarkably enhance microbial removal efficiency in aqueous treatment systems through sustained radical generation and improved photocatalytic bactericidal action.

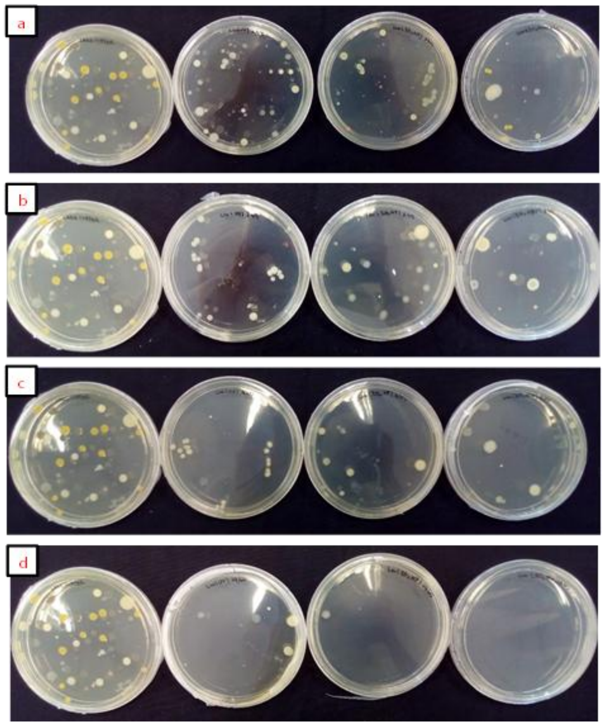

FIGURE 4. Lake water cultures from left to right: control, lake water treated with UV, lake water treated with TiO_2 nanoparticles, and lake water treated with TiO_2 nanowires under UV irradiation for (a) 2 hours, (b) 3 hours, (c) 4 hours, and (d) 24 hours.

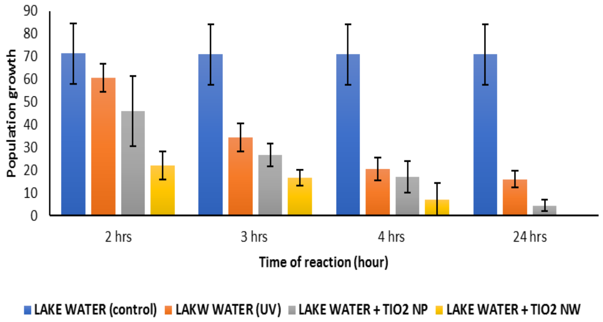

FIGURE 5. Changes in the population growth of lake water samples under UV irradiation at varying time intervals for photocatalysis process (mean ± SE, n = 3).

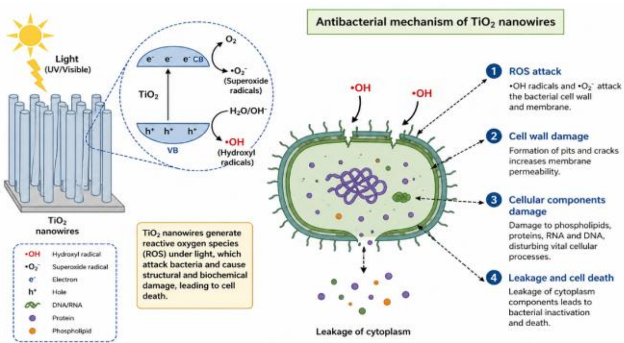

FIGURE 6. Antibacterial mechanism of TiO_2 nanowires.

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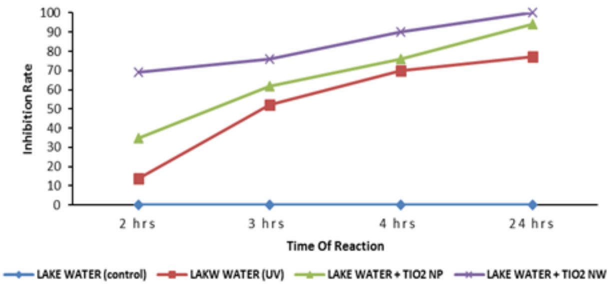

FIGURE 7. Inhibitory effect of various treating system in lake water samples at varying time intervals (n = 3).

Notably, the average microbial population was reduced further with the longer exposure time of irradiation, which was tally with the reported finding that the bactericidal effects induced by photocatalysis of TiO_2 could be affected by the irradiation time [24]; meanwhile, longer reaction time generally enhances the photocatalytic efficiency [15]. Among the samples, the lake water sample that treated with TiO_2 nanowires showed the least number of microbial growths compared to the samples treated with only UV light and TiO_2 nanoparticles. This enhanced performance can be attributed to the nanowires' one-dimensional structure, which provides a high surface-to-volume ratio that gives more active sites for photocatalytic reactions and improves adsorption of microbial cells and organic residues [11], [18]. Their elongated morphology also supports charge carrier separation by offering directed pathways that reduce recombination losses, while also enhancing light scattering, thereby producing more reactive species that are key agents inactivating microbes [11], [17].

By applying longer exposure time of irradiation and increasing the photocatalytic process, the average microbial population in both samples was significantly reduced as compared to the control samples. The samples that treated with TiO_2 nanowires tend to completely kill the microbes that present in the water after 24 hours. Besides that, Figure 7 displays that TiO_2 nanowires exhibited the highest efficiency of antibacterial activity, followed by TiO_2 nanoparticles and the control respectively. TiO_2 nanowires were shown to have almost 100% inhibitory efficiency, while TiO_2 nanoparticles and UV light were 94% and 77% accordingly. The prolonged irradiation of TiO_2 photocatalysts not only causes bacterial inactivation but also promotes the progressive mineralization of released intracellular organic residues into simpler inorganic end-products through sustained reactive oxygen species oxidation. For instance, TiO_2-mediated photocatalysis proceeds via a two-stage mechanism involving initial bacterial cell destruction followed by subsequent oxidation and mineralization of the residual organic biomass under sufficient irradiation time [25]. This observation is also supported by Shqier's research team to complete bacterial disinfection accompanied by total organic carbon reduction in TiO_2 photocatalytic treatment under solar-simulated radiation [26]. Similar behavior was observed in the present TiO_2 nanowire system, where no viable bacteria were detected after 24 h of irradiation in lake water samples, indicating that prolonged photocatalytic exposure facilitated. This may not only microbial inactivation but also extensive decomposition of bacterial organic constituents. By increasing the time of UV exposure to the nanoparticles, more OH radicals can be generated and thus enhance mineralization [27], [28].

Figure 8 demonstrates the antimicrobial effects of various treating systems in affecting the population growth of the *E. coli* samples respectively in the aspect of time for irradiation. From the graph, it has clearly shown that the microbial population was significantly decreased after the samples were irradiated under UV, TiO_2 nanoparticles and TiO_2 nanowires as compared to the control sample. Notably, the average microbial population was reduced further with the longer exposure time of irradiation. The *E. coli* sample that treated with TiO_2 nanowires was showed the least number of microbial growth compared to the samples that treated with only UV light and TiO_2 nanoparticles. Besides that, Figure 9 demonstrates TiO_2 nanowires exhibited the highest antibacterial activity, followed by TiO_2 nanoparticles and UV light respectively. TiO_2 nanowires were shown to have almost 100% inhibitory efficiency, while TiO_2 nanoparticles and UV light were 98.7% and 97.7% accordingly. For *E. coli* bacteria, there was not much difference in the antibacterial effects between UV light exposure alone and its combination with TiO_2. UV irradiation in the absence of TiO_2 reduced 97% of *E. coli* bacteria survival whereas the combination with TiO_2 achieved above 98%. From the results obtained, the majority of bacteria inactivation is imputable to the effect of TiO_2 photocatalyst. This proven again that the synthesized TiO_2 nanowire performed well on antibacterial and microbial activities.

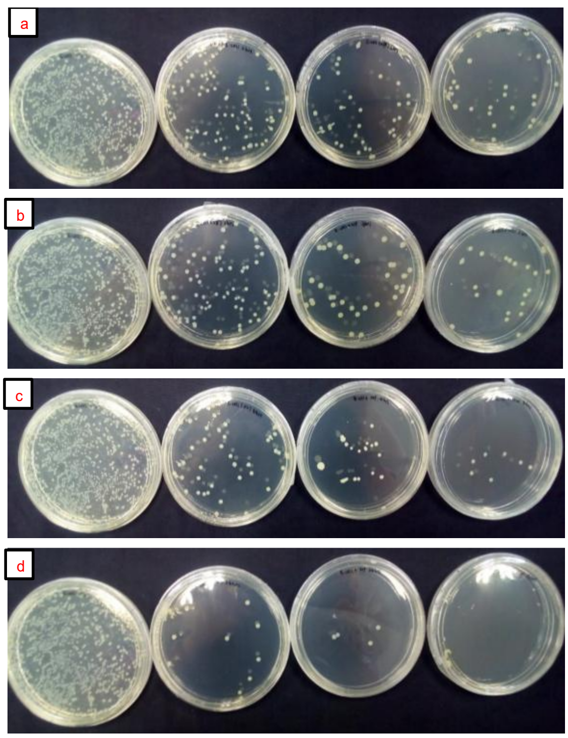

FIGURE 8. E. coli cultures from left to right: control, E. coli treated with UV, E. coli treated with TiO_2 nanoparticles, and E. coli treated with TiO_2 nanowires under UV irradiation for (a) 2 hours, (b) 3 hours, (c) 4 hours, and (d) 24 hours.

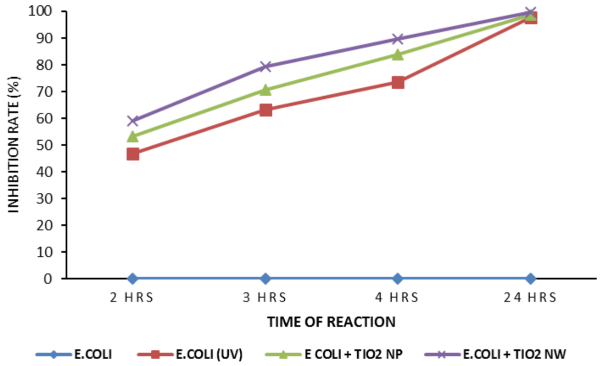

FIGURE 9. Changes in the population growth of *E. coli* samples under UV irradiation at varying time intervals for photocatalysis process (mean ± SE, n = 3).

IV. Conclusion

TiO_2 nanowires were successfully prepared using a simple hydrothermal method. The physical structure showed that the prepared nanowires result in one-dimensional nanosized wires. The UV-vis spectrum revealed that post-heat-treatment enhanced the crystallinity and light absorption ability of TiO_2 nanowires. Furthermore, TiO_2 nanowires showed a good performance in controlling the micropollutants in water. The addition of TiO_2 nanowires into the lake water enhanced the anti-bacterial activity and resulted in highest efficiency (almost 100%) within 24 hours in the inhibition test using *E. coli* sample under UV irradiation.

From a sustainability perspective, TiO_2 nanowires also offer practical advantages. Compared with dispersed TiO_2 nanoparticles, one-dimensional TiO_2 nanowire structures possess larger physical dimensions and interconnected fibrous morphology, this unique structure provides them with easier recovery through simple filtration or sedimentation, reducing energy use and secondary contamination. Nevertheless, the characteristic has improved the feasibility of large-scale water treatment and supports recoverability for repeated usage.

Overall, the results confirm the effectiveness of TiO_2 nanowire-based photocatalysis as a promising water purification method. Its application contributes to the development of environmentally friendly water treatment technologies, which strongly encourages SDG 6 (Clean Water and Sanitation) and SDG 3 (Good Health and Well-Being). Based on the well performance of photocatalysis, it is aimed to further apply the synthesized TiO_2 nanowires as catalyst in wastewater treatment or purification for various industries applications, supporting sustainable resource management. For future work, further investigation into the long-term stability, recoverability, environmental safety and regeneration efficiency of TiO_2 nanowires is recommended to fully validate their potential as a sustainable photocatalyst for water treatment applications.

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Author Contributions

Tan Sze Chi: Investigation, Methodology, Writing – Original Draft Preparation;

Evyan Yang Chia Yan: Supervision, Writing – Original Draft Preparation;

Le Hoang My: Writing – Review & Editing, Formatting;

Jie Vincent: Conceptualization, Writing – Review & Editing (TiO_2 Nanowires Treatment);

Chia Chin Hua: Conceptualization, Writing – Review & Editing (TiO_2 Nanowires Treatment);

Zhao Jinhui: Conceptualization, Writing – Review & Editing (Water Treatment).

Conflict of Interests

No conflict of interest was disclosed.

Ethics Statements

Ethical approval was not applicable to this research since it did not involve human participants, animals, or sensitive data.

Declaration of AI-Assisted Technologies in the Writing Process

During preparation of this work, the authors used Grammarly and ChatGPT in order to improve clarity and refine grammar and spelling. ChatGPT was also used to assist in generating FIGURE 6, which is based solely on the author's original scientific explanation and interpretation. After using these tools, the authors reviewed and edited the content as needed and took full responsibility for the content of the publication. These tools were not used to generate or interpret the scientific findings, analyses, or conclusions in the article.

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