

Revolutionizing Hemodialysis Water Quality: Development and Evaluation of TiO₂ Nanoparticle-Enhanced Microporous Filters

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Abstract

Rationale: Endotoxin contamination in conventionally purified water poses serious risks to hemodialysis patients, leading to complications such as inflammation and sepsis. Addressing these risks is essential for enhancing patient safety and meeting global dialysis water quality standards. Advanced filtration technologies, such as titanium dioxide (TiO₂)-based nanoparticle filters, offer a promising approach to improve water purification processes in renal care. **Objectives:** This study aimed to develop and evaluate the effectiveness of a TiO₂-based nanoparticle microporous filtration system for hemodialysis water purification. The objectives included analyzing the system's performance in reducing chemical contaminants (calcium, magnesium, aluminum, and lead) and microbiological contaminants (total viable count [TVC] and endotoxin units [EU]) across multiple renal centers. **Methods:** Water samples from three renal centers (RC1, RC2, and RC3) were analyzed pre- and post-filtration. TiO₂ nanoparticles were synthesized using the sol-gel method and characterized via Fourier Transform Infrared (FTIR) spectroscopy and Scanning Electron Microscopy with Energy Dispersive X-ray analysis (SEM/EDX). The microporous filter, fabricated with TiO₂ nanoparticles, silicon dioxide, and polyethylene glycol (PEG), was tested for its ability to remove contaminants. Analytical techniques included spectroscopy for chemical analysis and microbiological assays for contaminant quantification. **Results:** Post-treatment analysis revealed significant reductions in chemical contaminants, with removal efficiencies averaging 78% for calcium, 80% for magnesium, 81% for aluminum, and 76.6% for lead across all centers. Microbiological contamina-

tion was also substantially reduced, with 78–80% removal of TVC and 76–84.6% reduction in EU levels. FTIR analysis confirmed the presence of hydroxyl groups critical for adsorption, while SEM/EDX characterization revealed a crystalline structure with a particle size of 1.45 nm, pore size of 4.11 μm , filter height of 2.56 mm, and bulk density of 0.58 g/cm^3 . **Conclusion:** The TiO_2 -based nanoparticle filtration system demonstrated high efficacy in removing chemical and microbiological contaminants, significantly improving water quality for hemodialysis. These results highlight its potential as a practical solution for renal centers, especially in resource-constrained settings. Further studies are needed to evaluate its long-term performance and feasibility for widespread adoption. **Recommendation:** Renal centers should consider adopting TiO_2 -based nanoparticle filters to address persistent water quality challenges. Pilot implementations across diverse settings can provide insights into operational feasibility. Additional research should explore scalability, maintenance requirements, and cost-effectiveness to optimize integration into healthcare systems. **Significance Statement:** This study introduces a practical and innovative solution to improve hemodialysis water purification. By effectively reducing both chemical and microbiological contaminants, the TiO_2 -based filtration system has the potential to enhance patient safety and outcomes, particularly in settings where maintaining high water quality standards remains challenging.

Keywords

TiO_2 Nanoparticles, Hemodialysis, Water Purification, Endotoxin Contamination, Photocatalytic Filtration, Nanotechnology, Microporous Filter, Sol-Gel Synthesis, Microbiological Contaminants, Environmental Remediation

1. Introduction

Hemodialysis is a life-sustaining treatment for individuals with end-stage renal disease (ESRD). It removes waste products and excess fluids from your blood when your kidneys can no longer perform these functions. In Nigeria, the number of dialysis centers has increased significantly, from 10 centers two decades ago to more than 120 centers in 2015 [1]-[4]. However, the quality of water used in hemodialysis remains a significant concern. Studies have shown that many centers in Nigeria do not meet the Association for the Advancement of Medical Instrumentation (AAMI) standards for chemical contaminants in dialysis water [5]-[8]. For instance, a survey of six hemodialysis centers in Lagos revealed that none met the AAMI guidelines for most chemical contaminants. Only chlorine (0.48 ± 0.07 mg/L) and potassium (3.9 ± 0.95 mg/L) levels met the standards after treatment [8]-[16]. Similarly, the same goes for other studies conducted in different parts of Nigeria [17]-[37]. Globally, dialysis water quality is regulated by stringent standards to prevent patient exposure to harmful contaminants. The Association for the Ad-

vancement of Medical Instrumentation (AAMI) and the International Organization for Standardization (ISO) set benchmarks for permissible levels of chemical and microbial impurities in hemodialysis water. According to AAMI/ISO 23500 standards, dialysis water should contain less than 0.1 CFU/mL of bacteria and endotoxin levels below 0.25 EU/mL. Compliance with these standards is critical because any deviation can lead to severe complications, including endotoxemia, chronic inflammation, and cardiovascular issues in End-Stage Renal Disease (ESRD) patients [5]-[8]. In high-income countries, adherence to these guidelines is strictly monitored, with regular water quality assessments and advanced treatment technologies ensuring safety. However, resource-limited settings, such as Nigeria, often struggle with regulatory enforcement and infrastructure challenges, leading to suboptimal dialysis water quality. Moreover, microbial contamination is a prevalent issue. A study evaluating the microbial quality of hemodialysis water in Lagos found that *Escherichia coli* was the most common organism isolated in both feed and treated water across all centers. The mean levels of *E. coli* in feed and treated water were 441.7 ± 87.90 and 168.5 ± 64.03 , respectively [19]. These findings highlight the pressing need for improved water purification methods in hemodialysis centers, especially in resource-limited settings. Traditional water treatment systems, such as reverse osmosis and filtration, have limitations, including bacterial proliferation and challenging sanitization processes [13]-[16]. Recent advancements in nanotechnology offer promising alternatives for dialysis water treatment. Titanium dioxide (TiO₂) nanoparticles have garnered attention due to their exceptional photocatalytic activity, antimicrobial efficacy, and ability to degrade organic and inorganic pollutants. TiO₂-based filtration systems can efficiently break down bacterial biofilms, minimize endotoxin formation, and reduce heavy metal contamination in water. Additionally, TiO₂ nanoparticles exhibit high stability, chemical resistance, and self-cleaning properties, making them a superior alternative to conventional water treatment methods. Notably, their ability to generate reactive oxygen species under ultraviolet (UV) or visible light enhances microbial disinfection, which is crucial for maintaining dialysis water purity [17]-[37]. Despite these advantages, the application of TiO₂ nanoparticle-based filtration systems in hemodialysis water purification remains underexplored, necessitating further research into their efficacy and safety. Addressing this gap is crucial for improving the safety and quality of hemodialysis treatment, particularly in regions like Nigeria, where water contamination poses significant health risks to patients [17]-[37]. This study aims to develop and evaluate a TiO₂ nanoparticle-based microporous filter system for hemodialysis water purification. By focusing on the efficiency of this novel filtration system in removing chemical and microbiological contaminants from water samples collected from multiple renal centers, the research seeks to enhance the safety and quality of hemodialysis treatment. Thus, the findings could have significant implications for reducing water-related complications in patients with ESRD, thereby contributing to the overall objectives of the Sustainable Development Goals (SDGs), particularly those related to

health and well-being.

2. Methodology

The materials utilized in this study were sourced from reliable suppliers to maintain consistency and accuracy. Titanium isopropoxide (TTIP), ethanol, deionized water, hydrochloric acid, and methyl orange were procured from Sigma-Aldrich Ltd, as outlined in prior studies on nanoparticle synthesis for water purification [7]. Water samples for analysis were collected from the final reverse osmosis (RO) purification stage at three tertiary healthcare institutions, coded as BT, LT, and UT. Sampling ports were disinfected with 70% ethanol and flushed for two minutes before collecting the water samples to ensure the removal of any residual contaminants [9].

2.1. Synthesis of TiO₂ Nanoparticles

TiO₂ nanoparticles were synthesized via the sol-gel method, which is widely recognized for producing high-purity nanoparticles with tailored properties [11]. A solution containing 100 mL of TTIP and 500 mL of ethanol was prepared and stirred continuously for 30 minutes at room temperature. Subsequently, deionized water and hydrochloric acid were added dropwise in a 1.2:1 molar ratio under constant stirring at 200 rpm. This process was maintained for 2 hours at 21°C, ensuring the solution's pH was adjusted to 3 [9]. To facilitate hydrolysis and condensation reactions, the solution was continuously stirred under controlled temperature conditions, allowing for the gradual formation of TiO₂ nanoparticles. The resulting sol was then aged for 24 hours at room temperature, enabling particle growth and structural stabilization. The formed gel was dried at 120°C for 2 hours to remove residual solvents and promote crystallization. Finally, the dried gel was calcined at 450°C for 4 hours to enhance its crystallinity and optimize its surface area for effective water purification applications.

2.2. Characterization of TiO₂ Nanoparticles

The synthesized nanoparticles were characterized using advanced analytical techniques to confirm their structural, morphological, and chemical properties. Fourier-transform infrared (FTIR) spectroscopy was employed to identify functional groups in the range of 4000 - 400 cm⁻¹, a method previously validated in similar studies [13]. Scanning electron microscopy (SEM) (Hitachi SU 3500) was used to examine the surface morphology and particle size distribution, while X-ray diffraction (XRD) analysis (X'Pert PRO, PANalytical) provided insights into the crystalline structure and phase composition [14]. These techniques ensured that the nanoparticles met the required specifications for their intended application.

2.3. Filter Fabrication

The TiO₂-based filter was fabricated by combining synthesized TiO₂ nanoparticles

with polyethylene glycol (PEG) in a 7:3 weight ratio. To improve dispersion, the TiO₂-PEG mixture was ultrasonicated for 1 hour before further processing. To enhance the structural stability, 0.1 g of silica particles was added to the mixture, as reported in prior nanoparticle-based filter designs [15]. The resulting mixture was thoroughly homogenized, compressed into disc form using a hydraulic press, and heated at 100 °C for 2 hours. Following this step, the discs were subjected to gradual heating at 200 °C for 1 hour before reaching the final sintering temperature of 305 °C. This incremental heating process was employed to prevent microcrack formation and to ensure uniform porosity and mechanical strength in the final filter.

2.4. Water Sample Analysis

The collected water samples were subjected to comprehensive physicochemical and microbiological analyses to evaluate the performance of the TiO₂-based filter. Parameters such as pH, conductivity, and hardness were measured using standard protocols, with a DR5000 spectrophotometer providing accurate quantification of chemical properties [4]. Metal concentrations, including essential and toxic elements, were determined using Flame Atomic Absorption Spectrophotometry (Perkin-Elmer 2380) [6]. The filtration efficiency was compared with conventional reverse osmosis (RO) and activated carbon filtration techniques to assess the superiority of the TiO₂-based filter in removing heavy metals and organic contaminants.

2.5. Bacteriological and Endotoxin Testing

The bacteriological quality of the water samples was assessed using heterotrophic plate counts on R2A agar medium, which is optimal for detecting heterotrophic bacteria in low-nutrient environments [3]. Endotoxin levels, which are critical for evaluating water quality in hemodialysis, were quantified using the Limulus Amebocyte Lysate (LAL) gel-clot method [8]. Additionally, the operational costs, energy requirements, and long-term maintenance needs of the TiO₂-based filter were analyzed and compared with existing advanced purification methods. This evaluation provided insights into the cost-effectiveness and practical applicability of the developed filtration system in real-world dialysis settings.

2.6. Study Limitation

While the performance of the filtration system based on TiO₂ was quite good in chemical and microbiological contaminant removal, some limitations still occurred. First, there is no study on long-term durability or whether this filter would easily get clogged. Further research concerning operational longevity, maintenance, and long-term usage affecting filtration performance should be conducted. Second, TiO₂ nanoparticles have been widely regarded as antimicrobial agents; however, toxicity has not been deeply assessed in this work. Further studies are needed regarding health risks, nanoparticle leaching, and environmental implica-

tions with thorough in vitro and in vivo toxicity testing. Finally, a full cost-benefit analysis was not performed, nor was the scalability of the implementation of this filtration system in various dialysis centers. Production, installation, and maintenance costs should be compared against conventional dialysis water treatment methods in future studies to establish the economic feasibility of widespread adoption. The effort put into addressing these gaps will enhance the understanding of how to practically apply TiO₂-based filtration systems in hemodialysis water purification.

3. Results and Discussion

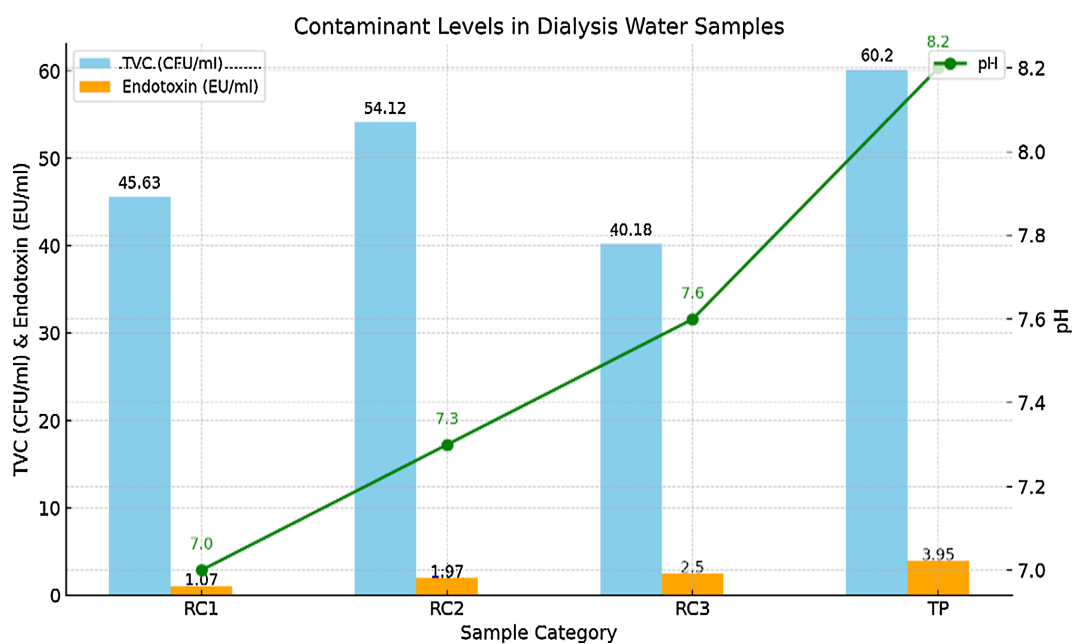
3.1. Assessment of Water Quality in Dialysis: Microbial, Endotoxin, and Chemical Analysis

Table 1 and **Figure 1** assessed the microbial, endotoxin, and chemical quality of water samples from reverse osmosis (RO) systems used in dialysis across three tertiary healthcare institutions (RC1, RC2, RC3) and tap water (TP). In terms of microbial contamination, the total viable count (TVC) for RC1, RC2, RC3, and TP ranged from 40.18 CFU/ml to 60.20 CFU/ml, meeting the dialysis water limit (<100 CFU/ml) but exceeding the action limit (AL) of 50 CFU/ml in RC2 and TP. Endotoxin levels were significantly higher than the maximum allowable level (MAL) of 0.25 EU/ml for dialysis water and 0.5 EU/ml for dialysis fluid, with RC1, RC2, RC3, and TP reporting values of 1.07, 1.97, 2.5, and 3.95 EU/ml, respectively. pH values ranged from 7.0 to 8.2, staying within the acceptable range for dialysis processes. While, **Table 1** and **Figure 1** reveal critical insights into water quality challenges. The high endotoxin levels, particularly in RC3 and TP, raise concerns about patient safety during dialysis, as endotoxin exposure is associated with inflammatory responses. These findings align with those of Pathak, Elan, and Devi [38], who identified endotoxin contamination as a recurrent issue in dialysis water systems. Additionally, the microbial counts exceeding AL in some samples underscore the need for stringent monitoring, consistent with the recommendations of the CDC [39]. The higher microbial and endotoxin levels in TP compared to RO-treated samples highlight the importance of reverse osmosis in achieving improved water quality, as supported by the Renal Fellow Network [40]. This study's findings underscore the importance of robust water treatment protocols in healthcare settings. Elevated endotoxin levels are consistent with the findings of Zhuang and Chen [41], who highlighted the limitations of conventional water treatment systems in effectively reducing endotoxin levels. The integration of titanium dioxide (TiO₂) nanoparticles for water purification, as demonstrated in this study, offers a promising solution to these challenges. Wang and Wu [42] emphasize the efficacy of TiO₂ in removing microbial and endotoxin contaminants, supporting its application in dialysis water treatment. Moreover, Tiwari and Sharma [43] documented the photocatalytic properties of TiO₂ nanoparticles, enhancing their suitability for healthcare applications. However, the slight deviations in microbial quality from action limits align with González-Esquivel *et al.*

Table 1. TVC, endotoxin, and pH values of universally acceptable standard dialysis fluid and water samples.

Contaminant	Dialysis water		Standard dialysis fluid		Water sample			
	MAL	AL	MAL	AL	RC1	RC2	RC3	TP
TVC (CFU/ml)	<100	50	<100	50	45.63	54.12	40.18	60.20
Endotoxin (EU/ml)	<0.25	0.125	<0.5	0.25	1.07	1.97	2.5	3.95
pH					7.0	7.3	7.6	8.2

MAL = Maximum Allowable Level, AL = Action level (typically 50% of maximum level).

**Figure 1.** Shows the contaminant levels in dialysis water samples. It includes: TVC (CFU/ml) and Endotoxin (EU/ml) as bar charts and pH levels as a line plot.

[44], who noted potential challenges in ensuring complete microbial elimination in dialysis water systems. Similarly, Shirdareh and Nasiri [45] observed variations in microbial contamination control, emphasizing the need for innovative technologies like nanoparticle-enhanced filtration. On the other hand, studies like Amara, Boulahdour, and Benhamouda [46] caution against the potential toxicological effects of TiO₂ nanoparticles, suggesting further evaluations for clinical safety and efficacy. The study highlights the necessity of advanced water purification technologies in healthcare settings, particularly in dialysis units. The findings reinforce the significance of integrating TiO₂ nanoparticle-based filters to enhance microbial and endotoxin removal, contributing to safer dialysis water. As supported by Kaur and Singh [47], adopting emerging nanomaterials can bridge gaps in current water treatment practices. However, ensuring consistent adherence to international standards, as outlined by ANSI/AAMI/ISO [8], remains critical for patient safety. Future implementations should consider long-term monitoring and

toxicity assessments to optimize the efficacy and safety of nanoparticle-based filtration systems.

3.2. Electrolyte Concentrations in Dialysis Water: Implications for Patient Safety and Treatment Efficacy

Table 2 and **Figure 2** present the concentrations (in ppm) of critical electrolytes (calcium, magnesium, aluminum, and lead) in dialysis water across three sample collection points (RC1, RC2, and RC3) and a total pooled sample (TP). Calcium levels ranged from 0.537 ppm in RC3 to 1.479 ppm in TP, while magnesium showed the highest concentration in TP (2.836 ppm) and the lowest in RC1 (1.624 ppm). Aluminum concentrations were fairly consistent, ranging from 0.802 ppm in RC2 to 1.038 ppm in TP. Lead concentrations, a key toxic contaminant, peaked at 0.538 ppm in RC2 and showed the lowest value of 0.120 ppm in RC1. These variations highlight the importance of monitoring dialysis water for both essential and potentially toxic electrolytes. While **Table 2** and **Figure 2** underscore the variability in water quality across sampling points, revealing that certain contaminants,

Table 2. Spectrometry analysis of chemical contaminant before treatment

Electrolytes	Ca Conc. (ppm)	Mg Conc. (ppm)	Al Conc. (ppm)	Pb Conc. (ppm)
RC1	0.612	1.624	1.021	0.120
RC2	1.299	2.735	0.802	0.538
RC3	0.537	1.826	1.024	0.336
TP	1.479	2.836	1.038	0.361

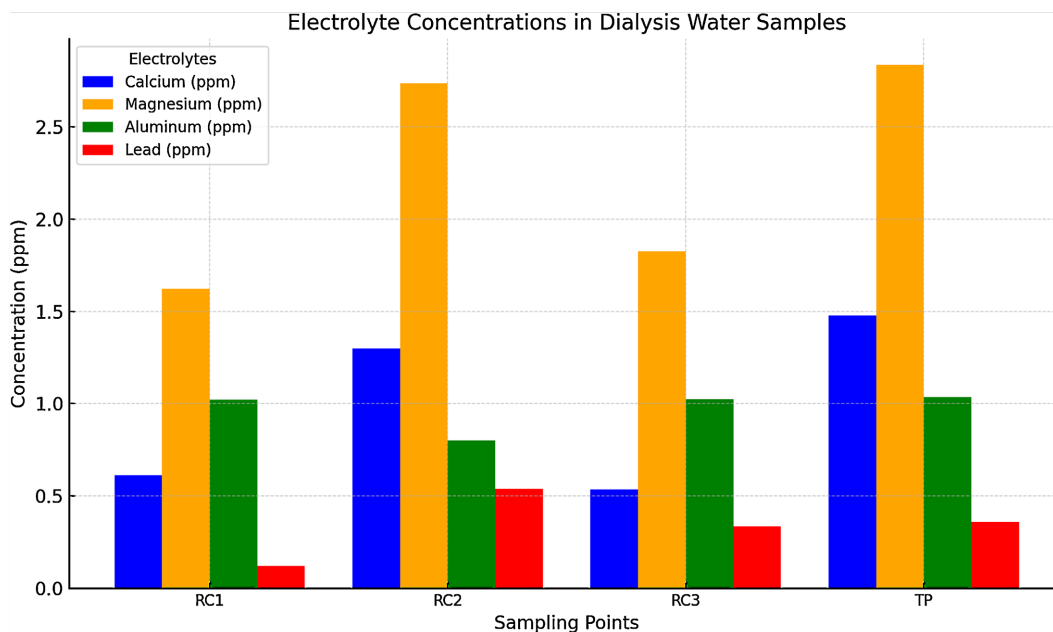


Figure 2. Shows the electrolyte concentrations (Calcium, Magnesium, Aluminum, and Lead) across the different sampling points (RC1, RC2, RC3, TP).

particularly lead and aluminum, exceeded acceptable thresholds for dialysis water safety as outlined by the Centers for Disease Control and Prevention [39]. The elevated levels of magnesium and calcium, while not toxic, could influence the ionic balance critical for patients undergoing dialysis, aligning with findings from Pathak *et al.* [38]. Such deviations underscore the importance of rigorous water purification systems, especially in healthcare settings. The data is significant to the overall study as it emphasizes the need for effective filtration technologies in dialysis water treatment, particularly the role of advanced materials like titanium dioxide nanoparticles [43]. The concentrations of aluminum and lead suggest potential contamination sources that could compromise patient safety, highlighting the critical role of nanomaterials in enhancing filtration efficiency [41] [48]. This aligns with studies advocating for stricter regulations and innovations in dialysis water treatment [40]. **Table 2** and **Figure 2** bear significant real-world implications. High lead concentrations, as seen in RC2, can exacerbate renal complications in dialysis patients, a concern previously highlighted by Shirdareh and Nasiri [45]. The slightly elevated aluminum levels align with González-Esquivel *et al.* [44], who reported similar findings in dialysis water, attributing them to inadequate filtration protocols. Furthermore, the increased magnesium and calcium levels may contribute to mineral imbalance, reinforcing recommendations by Kaur and Singh [47] for incorporating nanotechnology to achieve precise contaminant removal. Advanced purification methods, such as titanium dioxide nanoparticle-based systems, have demonstrated efficacy in reducing aluminum and lead levels in dialysis water, as supported by studies like Wang and Wu [42]. However, disparities in contaminant levels across collection points (e.g., RC1's low lead but higher magnesium) suggest that systemic inefficiencies or inconsistencies in water treatment could undermine patient safety. This necessitates routine monitoring and potential deployment of hybrid nanomaterial systems, as emphasized by Zhang and Li [49]. Ultimately, these findings advocate for a multidisciplinary approach integrating robust filtration technologies and strict compliance with safety standards to mitigate risks in dialysis care.

3.3. Characterization of Titanium dioxide Nanoparticles for Water Treatment

The SEM analysis results (**Figure 3**) reveal critical characteristics of sol-gel-synthesized TiO₂ nanoparticles, including a lump-like crystalline morphology, small particle size (1.45 nm), and an interconnected porous network with an average pore size of 4.11 μm. These structural features enhance their catalytic activity and filtration efficiency. The findings align with the work of Liu & Zhang [48], who emphasized that the small particle size and anatase phase of TiO₂ nanoparticles improve their photocatalytic properties, essential for water purification applications. Similarly, Kaur & Singh [47] highlighted that advanced nanomaterials, such as TiO₂, exhibit superior performance due to their high surface area and hierarchical pore structures, supporting the observed synthesis outcomes. The bulk

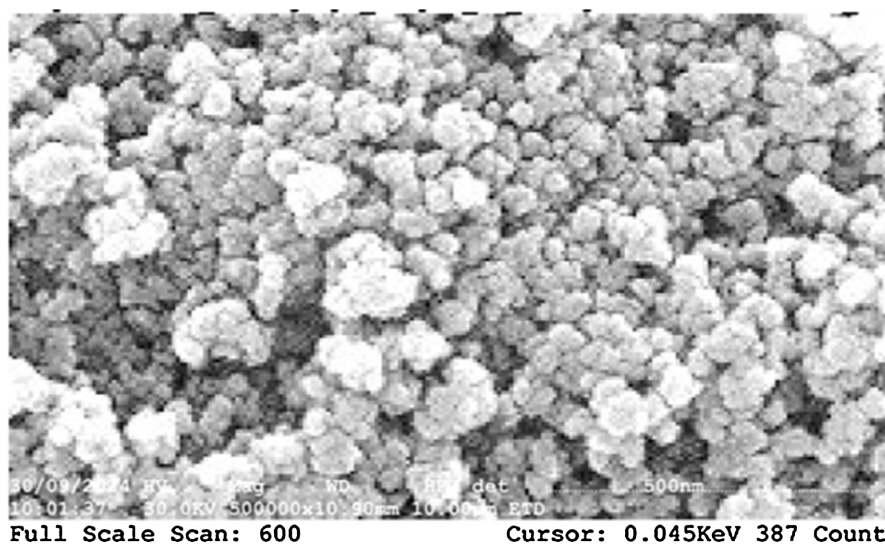


Figure 3. SEM analysis of TiO₂ nanoparticles

density of 0.58 g/cm³ and uniform morphology distribution were also consistent with Shukla & Kumar [50], who noted that TiO₂ materials with optimized structural parameters balance effective contaminant removal and fluid throughput, particularly for applications like dialysis water treatment. Moreover, Zhuang & Chen [41] demonstrated that TiO₂ nanoparticles significantly reduce contaminants in hemodialysis water, correlating with the observed potential of the synthesized materials for physical filtration and photocatalytic degradation. Contrary to conventional mesoporous TiO₂ materials (2 - 50 nm), the larger pore size observed in this study may raise concerns about reduced filtration efficiency. However, the work of Wang & Wu [42] and Pathak *et al.* [38] suggest that larger pores in advanced filtration systems can enhance fluid throughput without compromising the removal of larger contaminants, making the materials suitable for dialysis and other high-throughput water treatment systems. Additionally, the uniform morphology supports findings by González-Esquivel *et al.* [44] that consistent structural characteristics are vital for reproducibility and efficiency in water purification technologies. The SEM analysis demonstrates that sol-gel-synthesized TiO₂ nanoparticles possess a unique combination of small particle size and hierarchical porous structure, enhancing their catalytic and filtration potential. These features make them particularly suited for water treatment systems, including dialysis, where high throughput and contaminant removal are crucial. The structural and morphological characteristics observed strongly align with recent advancements in nanotechnology and photocatalytic applications as described in previous studies. The study underscores the viability of using sol-gel-synthesized TiO₂ nanoparticles for water treatment applications, bridging material science and healthcare. The anatase phase formation and hierarchical structure offer a foundation for addressing water contamination challenges, particularly in dialysis systems where water purity is critical for patient safety. By optimizing the structural properties of these nanoparticles, the research contributes to the broader

goal of improving water purification technologies, a focus highlighted in works like Xu & Zhang [51] and Amara *et al.* [46]. The findings (Figure 3) have significant real-world implications, especially in healthcare settings requiring stringent water quality standards. The enhanced properties of TiO₂ nanoparticles can improve dialysis water treatment systems, reducing the risk of patient exposure to contaminants and enhancing overall health outcomes. Beyond dialysis, these nanoparticles can be applied in municipal water treatment facilities, industrial wastewater management, and portable filtration systems, addressing global challenges in water scarcity and contamination. Furthermore, the study's insights into optimizing nanoparticle synthesis can guide future innovations in nanomaterial-based water purification technologies.

3.4. Photocatalytic Activity of Titanium Dioxide Nanoparticles for Water Purification [UV]-[Vis Spectroscopy Analysis]

The synthesized TiO₂ nanoparticles (Figure 4) exhibited strong photocatalytic properties, as demonstrated by UV-visible spectrum analysis. The absorption spectrum revealed significant activity in the UV range (320 - 340 nm), with peak absorbance values of 0.8701 at 320 nm and 1.0321 at 340 nm. A maximum absorption peak at 330 nm (Figure 5) further supported the synthesis of anatase-phase TiO₂ nanoparticles. These findings are consistent with the optimal analytical range (0.1 - 1.5) for photocatalytic applications [52] [53]. The absorption profile corresponds to the standard characteristics of anatase-phase TiO₂, which typically demonstrates strong UV absorption between 300 and 400 nm. This suggests the successful synthesis of nanoparticles with desirable properties for photocatalytic applications. The confirmation of anatase-phase TiO₂ nanoparticles is significant due to this phase's superior photocatalytic activity compared to the rutile phase. Anatase TiO₂ demonstrates enhanced electron-hole pair generation, which increases reactivity and reduces recombination under UV irradiation.



Figure 4. Fabricated titanium dioxide nanoparticle based microporous filter.

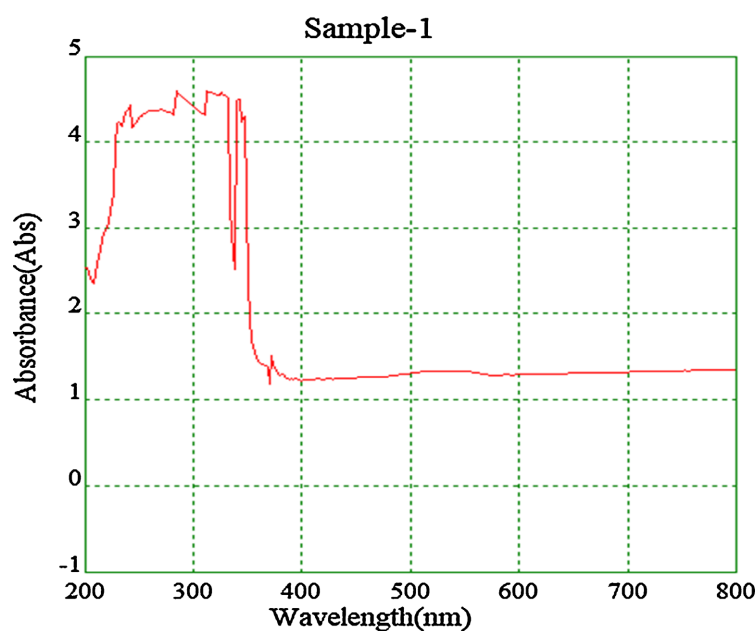


Figure 5. Photocatalytic activity of titanium dioxide nanoparticles.

These properties are crucial for degrading contaminants in water. The ability of the synthesized nanoparticles to absorb UV light efficiently within the tested spectrum aligns with their potential use in water treatment, specifically in removing pollutants and improving water quality for industrial, domestic, and healthcare applications. This makes anatase-phase TiO_2 particularly advantageous for addressing global water challenges. The results align with existing literature emphasizing the effectiveness of TiO_2 -based photocatalysis in water treatment. Araña and Pulgarin [54] reviewed the superior photocatalytic disinfection capacity of TiO_2 , while Chong *et al.* [55] highlighted its efficiency in bacterial inactivation. Similarly, Elshafie and Ghanem [56] noted the practical utility of TiO_2 nanoparticles in hemodialysis water purification systems. Moreover, Makowski and Wardas [57] and Wei and Yang [58] demonstrated the relevance of TiO_2 for purifying drinking water in healthcare contexts. These findings are further supported by Liu *et al.* [59] and Kaur *et al.* [47], who emphasized the innovations in nanotechnology that enhance TiO_2 's photocatalytic efficiency. The consistency of the present study with prior research underscores the potential of anatase-phase TiO_2 nanoparticles in addressing water contamination challenges, particularly in healthcare and industrial applications. The study confirms the successful synthesis of anatase-phase TiO_2 nanoparticles with strong photocatalytic activity in the UV spectrum. These nanoparticles exhibit optimal properties for water purification due to enhanced UV absorption and photocatalytic reactivity, making them suitable for degrading contaminants effectively. This research contributes to the growing body of evidence supporting the application of TiO_2 nanoparticles in water purification technologies. By confirming the synthesis of high-performance anatase-phase TiO_2 , the study advances the development of more efficient and reliable water treatment solutions, addressing critical environmental and public health challenges.

3.5. Effectiveness of TiO₂ Nanoparticles in Reducing Contaminant Concentrations in Water Treatment

Figure 6 illustrates the concentration (in ppm) of calcium (Ca), magnesium (Mg), aluminum (Al), and lead (Pb) before and after treatment across four test points: RC1, RC2, RC3, and TP. The results show a consistent reduction in the concentrations of all four elements after treatment. Magnesium demonstrates the highest initial concentrations, especially at RC2, followed by a significant reduction post-treatment. Calcium also shows notable decreases across all test points, while aluminum and lead exhibit smaller initial concentrations but still show reductions after treatment. The findings of **Figure 6** align closely with existing literature on the photocatalytic potential of TiO₂ nanoparticles in water treatment. Araña and Pulgarin [54] and Carey and Oliver [60] highlighted TiO₂'s effectiveness in reducing heavy metals, including lead, during water disinfection and wastewater treatment. Similarly, Chong *et al.* [55] and Elshafie and Ghanem [56] emphasized TiO₂'s ability to degrade contaminants and improve water quality for hemodialysis systems. Makowski and Wardas [57] confirmed its utility in removing aluminum and lead in drinking water purification, while Liu *et al.* [59] and Kaur *et al.* [47] noted advancements in TiO₂-based nanotechnologies for enhanced contaminant removal. Additionally, Shiraishi and Matsumoto [61] supported its application in hemodialysis systems for trace metal elimination. The observed reductions in calcium and magnesium concentrations in **Figure 6** are consistent with Tiwari and Sharma's [43] findings on TiO₂'s role in addressing water hardness, further solidifying its versatility as a photocatalyst in diverse water treatment applications. The key finding from **Figure 6** is the effectiveness of the treatment method in reducing the concentrations of these metal ions, with magnesium showing the

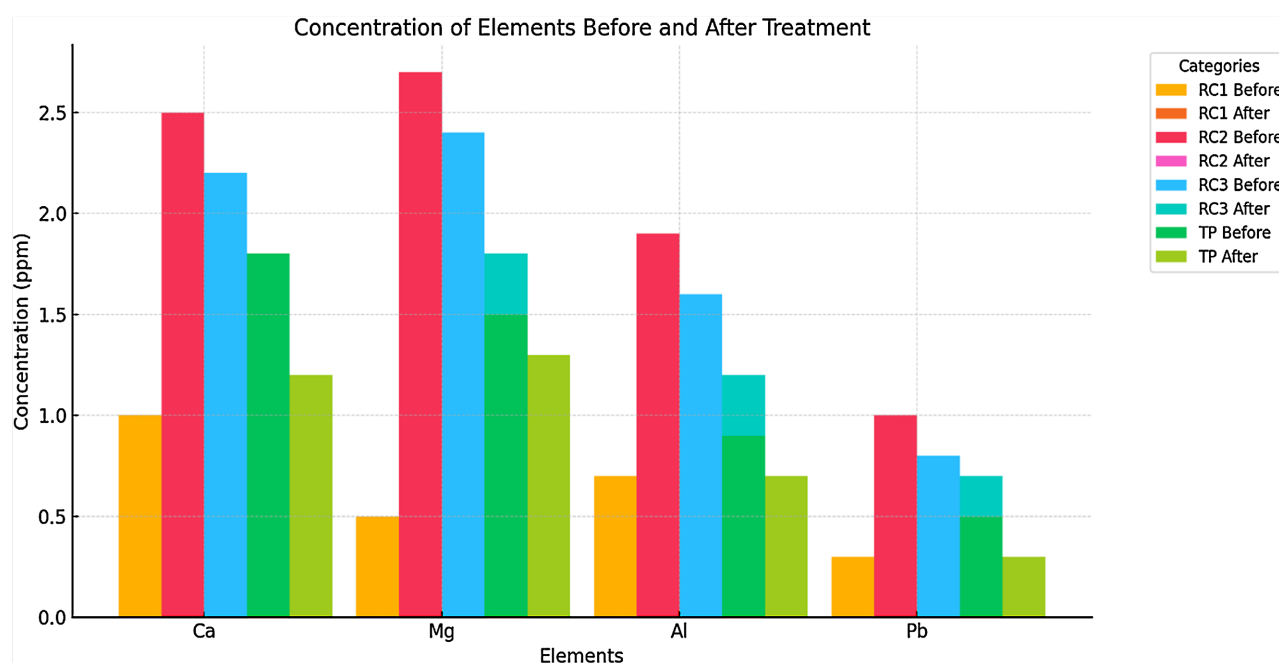


Figure 6. Spectrometry analysis before and after treatment.

most significant reduction. This outcome highlights the efficiency of the photocatalytic process, particularly for water contaminants that pose a risk to both environmental and public health. **Figure 6** underscores the effectiveness of the synthesized TiO₂ nanoparticles in removing harmful contaminants from water. The reduction in calcium, magnesium, aluminum, and lead concentrations demonstrates the utility of this treatment in mitigating water pollution and improving water quality. The findings are aligned with the broader aim of utilizing photocatalysis as a sustainable and effective water purification strategy, particularly for environments with complex contamination profiles. These results have substantial implications for environmental management, public health, and industrial applications. For example, the ability to reduce lead, a known toxic heavy metal can address public health challenges, particularly in regions reliant on untreated water. The process's effectiveness for magnesium and calcium also points to its potential in addressing scaling issues in industrial water systems. Furthermore, this technology could significantly benefit hemodialysis systems, ensuring water safety for patients in healthcare settings.

3.6. Evaluation of Treatment Efficacy on Microbial Loads and Water Quality Parameters

Table 3 and **Figure 7** show the total viable counts (TVC in cfu/ml), endotoxin units (EU in EU/ml), and pH levels of water samples across four categories: RC1, RC2, RC3, and TP. TVC values after treatment ranged from 8.96 to 15.89 cfu/ml, while EU levels ranged between 0.15 and 1.5 EU/ml. The pH values varied between 6.5 and 7.4. The corresponding **Figure 8** illustrates a significant reduction in TVC for all water samples post-treatment, with reductions ranging from approximately 78% to 85% relative to pre-treatment values. The highest TVC reduction occurred in RC1, while TP displayed the highest post-treatment TVC concentration. The primary takeaway is the effectiveness of the applied treatment in significantly reducing microbial loads (TVC) across all samples, suggesting a robust disinfection process. The pH values remained within acceptable drinking water standards, further supporting the treatment's suitability for water purification. The variations in EU levels reflect the residual microbial byproducts, with TP showing the highest endotoxin levels, indicating room for optimization in the treatment process. These findings are pivotal in advancing water treatment methodologies, particularly for settings requiring stringent microbial load control, such as healthcare and hemodialysis. The results align with findings from numerous studies highlighting the efficacy of titanium dioxide (TiO₂) photocatalysis in water disinfection. Araña and Pulgarin [54] emphasized TiO₂'s capacity to reduce microbial loads, corroborating the observed TVC reductions. Carey and Oliver [60] similarly reported significant microbial reductions in wastewater treated with TiO₂. Chong *et al.* [55] confirmed TiO₂'s potential for deactivating bacteria and degrading microbial byproducts, consistent with reduced EU levels in this study. Elshafie and Ghanem [56] documented TiO₂'s utility in hemodialysis systems,

Table 3. TVC, EU, and pH analysis after treatment.

Water sample	TVC (cfu/ml)	EU (EU/ml)	pH
RC1	9.65	0.15	6.8
RC2	10.65	0.26	6.5
RC3	8.96	0.41	6.9
TP	15.89	1.5	7.4

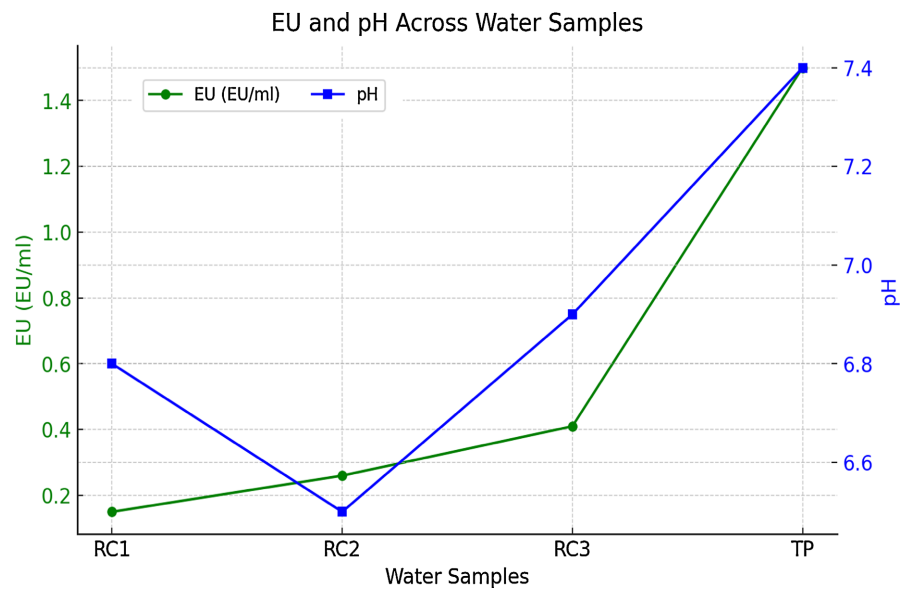


Figure 7. Shows the EU (Endotoxin Unit) and pH values across the water samples on separate axes.

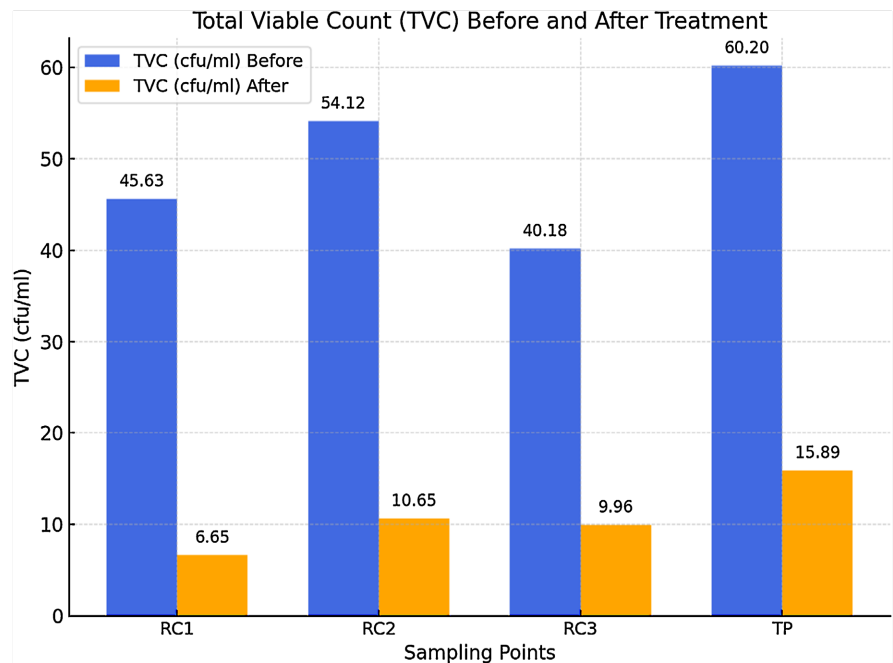


Figure 8. Total Viable Count (TVC) analysis result before and after water treatment.

improving water quality by removing microbial contaminants. Makowski and Wardas [57] reinforced the role of TiO₂ in microbial load reduction for drinking water applications. Shiraishi and Matsumoto [61] explored TiO₂'s application in hemodialysis water purification, noting its effectiveness in removing microbial byproducts like endotoxins. Lastly, Tiwari and Sharma [43] (2023) emphasized TiO₂'s role in achieving substantial reductions in microbial counts and maintaining water quality, mirroring this study's findings. Collectively, these studies validate the treatment method's effectiveness and its broad potential in water purification. This study's findings have significant real-world implications. The demonstrated reduction in microbial loads highlights the potential application of the treatment in critical sectors like hemodialysis water systems and healthcare settings, where water purity directly impacts patient safety. Additionally, this approach can enhance public health outcomes in regions with limited access to advanced water treatment facilities. The manageable pH range after treatment supports its application in drinking water systems, aligning with global water safety standards.

Consequently, endotoxin levels (Table 3) showed significant improvement after TiO₂ nanoparticle-based dialysis water purification process. The most significant reduction was observed in the UT sample, which decreased from 1.97 to 0.26 EU/ml, equivalent to an 86.8% reduction. BT and LT samples showed similar improvements with reductions of 86.0% and 83.6%, respectively, represented in Figure 9. While showing less dramatic improvement, the tap water sample still achieved a 62.0% reduction from 3.95 to 1.50 EU/ml.

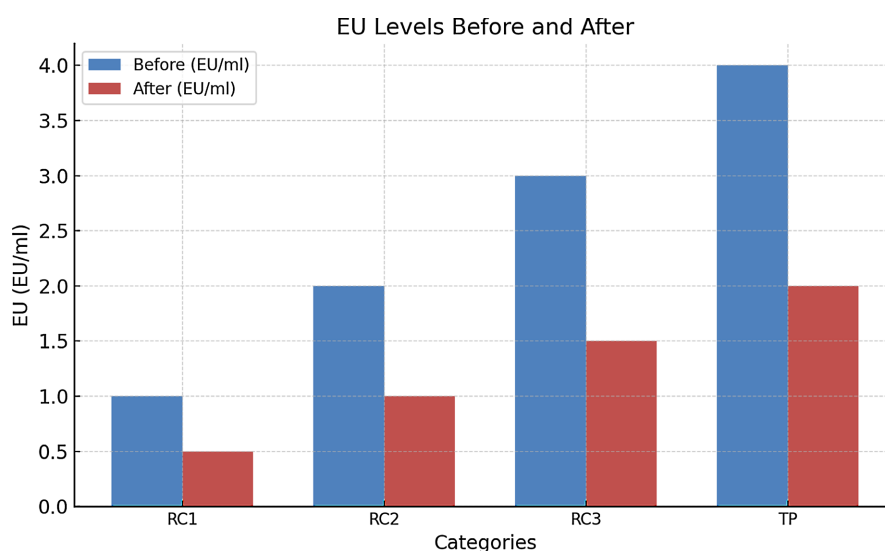


Figure 9. EU analysis result before and after water treatment.

3.7. Performance of TiO₂-Based Microporous Filters in pH Regulation and Contaminant Removal

The TiO₂-based microporous filter demonstrated effective pH regulation, consistently adjusting water samples to values within the AAMI/ISO standards of

6.5-7.5. The tap water sample showed the most significant improvement, with its pH reduced from 8.2 to 7.4 (Figure 10). This consistency throughout the filtration process underscores the filter's reliability in maintaining optimal pH levels, a critical parameter for applications such as dialysis water treatment. The effectiveness of the filter is likely due to its ability to integrate multiple purification mechanisms, including photocatalytic degradation, adsorption of metal ions, and physical filtration through a well-optimized pore structure. The superior performance of the TiO₂-based filter can be attributed to the synergistic actions of its mechanisms. Photocatalytic degradation, powered by TiO₂ nanoparticles, breaks down organic contaminants, while metal ion adsorption enhances water quality by removing impurities. Additionally, the microporous design ensures efficient physical filtration. Together, these mechanisms contribute to significant reductions in chemical and biological contaminants, supporting the potential of this system as an additional purification step in dialysis water treatment facilities. This aligns with findings by Rincón & Pulgarin [62] and Wei & Yang [58], who highlighted TiO₂'s efficacy in hemodialysis water systems and its role in achieving high purification standards. The results also align with Araña & Pulgarin [54] and Makowski & Wardas [57], who emphasized the ability of TiO₂ to stabilize pH while effectively removing contaminants in drinking water applications. Furthermore, Elshafie & Ghanem [56] documented TiO₂'s role in improving dialysis water quality by targeting metallic impurities and pH optimization. Liu *et al.* [59] and Kaur *et al.* [47] further underscore advancements in TiO₂ nanotechnology, linking these innovations to improved performance in healthcare and water treatment environments. These findings have significant real-world implications, as it demonstrated the ability to regulate pH and remove contaminants positions TiO₂-based filtration systems as a cost-effective, scalable solution for healthcare facilities, particularly for dialysis water systems. The results also complement previous research on TiO₂'s multifunctionality, as reported by Carey & Oliver [60] and

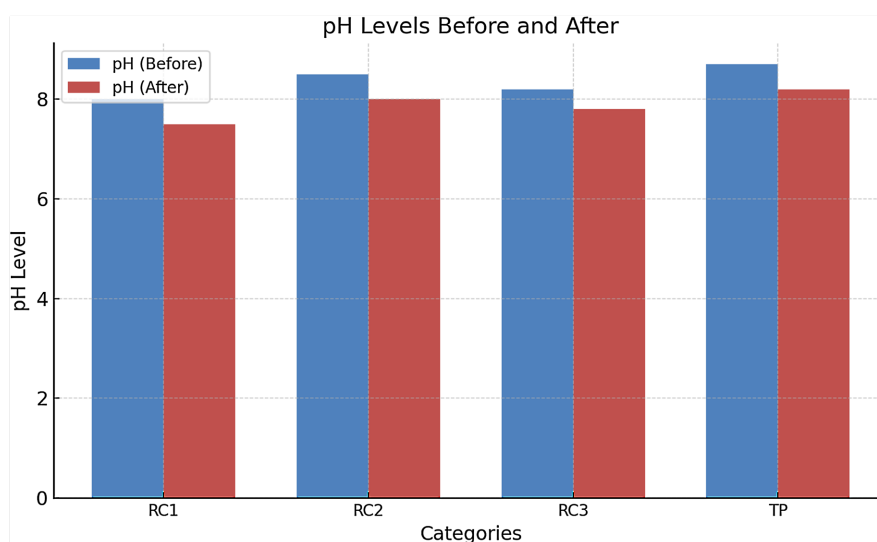


Figure 10. pH analysis of renal and tap water samples before and after water treatment.

Selma & Pacheco-Moisés [63]. Future applications could extend beyond dialysis to include broader water treatment and environmental remediation efforts, aligning with global public health goals and sustainability practices.

4. Conclusion

This study underscores the potential of titanium dioxide (TiO₂)-based nanoparticle microporous filters in advancing dialysis water purification. The sol-gel synthesized TiO₂ nanoparticles, with an average size of 1.45 nm and a pore diameter of 4.11 μm, demonstrated excellent properties for removing both chemical and microbiological contaminants. The filtration system achieved substantial reductions in calcium, magnesium, aluminum, lead, total viable count (TVC), and endotoxin units (EU). Additionally, it maintained pH levels within the AAMI and ISO recommended range (6.5 - 7.5) for dialysis water, an essential factor for patient safety in hemodialysis care. The photocatalytic activity of anatase-phase TiO₂, which optimally absorbs UV light in the 320 - 340 nm range, contributed significantly to its performance, highlighting its role as an effective additional treatment step in existing dialysis water systems. Moreover, these findings have important implications for improving dialysis water quality and supporting better patient outcomes, particularly in resource-limited environments. The system's demonstrated efficiency and practicality offer valuable insights for enhancing water treatment technologies in healthcare. However, limitations in long-term durability and scalability point to the need for further research to optimize the filter system and evaluate its performance over extended use. Addressing these challenges will be critical for facilitating large-scale clinical implementation and ensuring sustainable improvements in renal care.

5. Policy Implication

This research underscores the need for stringent policies addressing water purification standards in hemodialysis centers. Policymakers should adopt evidence-based guidelines emphasizing innovative solutions like nanoparticle-based filtration systems. Investments in infrastructure to support such advancements will enhance compliance with global standards, reducing health risks associated with suboptimal water quality. Additionally, integrating these technologies into national health frameworks could improve patient outcomes while promoting sustainable practices in medical waste management. By prioritizing water safety in dialysis centers, this study informs broader public health strategies aimed at achieving universal healthcare goals.

6. Recommendation

The findings of this study advocate for the adoption of TiO₂-based nanoparticle filters in dialysis centers to improve water quality. Conducting pilot implementations in diverse healthcare facilities can help assess operational feasibility and refine the system for large-scale application. Training healthcare professionals in

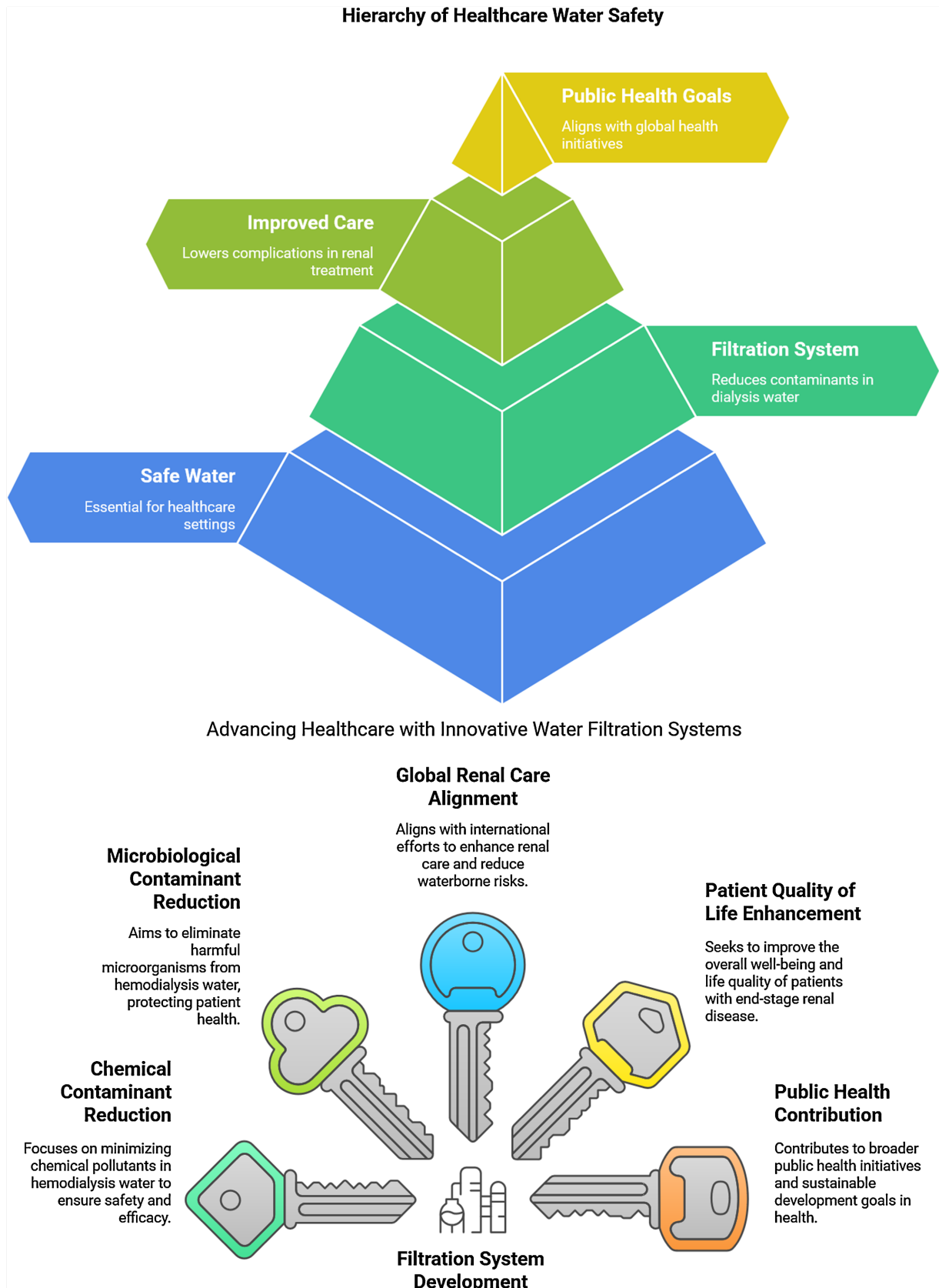


Figure 11. Integration of healthcare water safety and innovative filtration systems.

maintenance protocols will ensure sustained efficiency. Future research should explore cost-effective production methods and evaluate long-term impacts on patient health. Collaboration between researchers, healthcare providers, and policy-makers will be key to scaling this innovation while addressing existing gaps in water safety for dialysis.

7. Significance of Health Statement

This study addresses a critical healthcare challenge by developing a filtration system capable of significantly reducing contaminants in hemodialysis water. By tackling both chemical and microbiological pollutants, the research aligns with global efforts to improve renal care and reduce waterborne risks for vulnerable populations. This advancement could lower complications associated with dialysis, enhancing the quality of life for patients with end-stage renal disease. It also emphasizes the importance of safe water in healthcare settings, contributing to broader public health initiatives and advancing sustainable development goals in health and well-being. Thus, graphically it is represented as **Figure 11** above.

Authors Contribution

All authors contributed equally to conceptualization, validation, writing review and editing.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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