A Prototype Design and Experimental Analysis of Reverse Osmosis Technology for Drinking Water Treatment Systems

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Abstract : The increasing demand for safe drinking water, particularly in regions relying on contaminated river sources, necessitates the development of efficient water treatment technologies. This study aims to design, implement, and evaluate a prototype drinking water treatment system based on reverse osmosis (RO) technology using Musi River water as the raw water source. The proposed system employs an eight-stage treatment configuration consisting of pre-treatment (sediment, granular activated carbon, and carbon block), core-treatment (RO membrane), and post-treatment (post carbon, mineralization, alkaline filter, and ultraviolet sterilization). Initial laboratory analysis of raw water indicated that several parameters, including turbidity, color, and iron (Fe), exceeded acceptable limits. Following chemical pre-treatment, the water quality met clean water standards and was further processed using the RO system. Performance evaluation results demonstrate significant improvements in water quality, including a reduction in total hardness from 278.47 ppm to 1.21 ppm, bicarbonate alkalinity from 291.16 ppm to 13.86 ppm, and complete removal of iron (0 ppm). Total Dissolved Solids (TDS) decreased to 21.65 ppm, while pH remained stable within the acceptable range (7.10). The results confirm that the proposed RO-based system is highly effective in removing physical, chemical, and microbiological contaminants, producing water that meets national drinking water standards. Therefore, this system offers a reliable and scalable solution for decentralized drinking water treatment, particularly in areas with limited access to clean water sources.

Keywords: Reverse osmosis, drinking water treatment, river water, water quality, membrane technology

1. Introduction

Water is a fundamental human necessity, and its availability in adequate quantity and quality is essential for sustaining life and public health. The increasing global population has significantly intensified the demand for clean water, particularly for drinking purposes. However, many regions continue to face challenges in accessing safe drinking water due to pollution, urbanization, and limited infrastructure [1], [2]. Surface water sources, such as rivers, remain widely utilized for domestic activities

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including bathing, washing, and sanitation. Despite their availability, river water is often contaminated with physical, chemical, and biological pollutants, rendering it unsafe for direct consumption without proper treatment [3], [4].

The degradation of river water quality is primarily driven by industrial discharge, agricultural runoff, and domestic waste, which introduce contaminants such as heavy metals, pathogens, organic compounds, and suspended solids [5], [6]. Consequently, effective water treatment technologies are required to ensure compliance with drinking water standards, such as those established by the World Health Organization (WHO) and national regulatory frameworks [7]. In Indonesia, drinking water quality standards are regulated under the Ministry of Health Regulation No. 2 of 2023, which specifies permissible limits for various physical, chemical, and microbiological parameters.

Various water treatment methods have been developed to address these challenges, including conventional filtration, coagulation-flocculation, disinfection, and membrane-based technologies [8]. Among these, reverse osmosis (RO) has emerged as one of the most effective and widely adopted technologies for water purification. RO utilizes a semi-permeable membrane to remove dissolved solids, microorganisms, and other contaminants by applying pressure to overcome osmotic pressure [9], [10]. This process is capable of producing high-quality drinking water with significant removal efficiencies for total dissolved solids (TDS), heavy metals, bacteria, and viruses [11].

The advantages of RO technology include its high separation efficiency, flexibility in treating various water sources, and ability to meet stringent water quality standards [12]. Additionally, RO systems can be integrated with pre-treatment and post-treatment processes such as ultrafiltration (UF) and ultraviolet (UV) disinfection to enhance performance and ensure microbial safety [13], [14]. However, despite its effectiveness, RO technology also presents several challenges, including membrane fouling, energy consumption, operational costs, and brine disposal [15], [16]. These challenges necessitate further research to optimize system design, improve efficiency, and reduce operational constraints, particularly for small-scale or decentralized applications.

Recent studies have focused on the development of compact and cost-effective RO systems suitable for rural and remote areas, where centralized water treatment facilities are often unavailable [17], [18]. Prototype-based approaches allow researchers to evaluate system performance under real conditions and identify technical limitations prior to large-scale implementation [19]. Furthermore, integrating monitoring systems and optimizing operational parameters can significantly enhance system reliability and sustainability [20].

Based on these considerations, this study aims to design, implement, and evaluate a prototype drinking water treatment system based on reverse osmosis technology using river water as the raw water source. The study focuses on assessing the effectiveness of the RO process in improving water quality, comparing the treated water against applicable drinking water standards, and identifying technical challenges associated with prototype-scale implementation. The findings are expected to contribute to the development of efficient, scalable, and sustainable water treatment solutions, particularly for decentralized applications.

2. METHODOLOGY

This study adopts a systematic and experimental approach to design, implement, and evaluate a prototype drinking water treatment system based on reverse osmosis (RO) technology. The overall research methodology is structured in several sequential stages, as illustrated in the research flowchart, starting from preliminary studies to system testing and performance evaluation, as in figure 1.

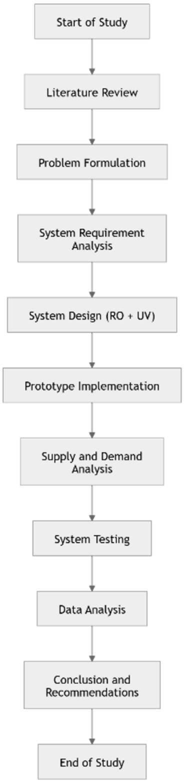

Figure 1. Flowchart

The initial stage involves a comprehensive literature review to gather relevant theoretical foundations and empirical findings related to water treatment technologies, particularly reverse osmosis systems. Sources include scientific journals, reference books, technical standards, and previous research studies. This stage aims to identify research gaps, understand system design parameters, and establish a scientific basis for the development of the proposed prototype.

Following the literature review, the research problem is formulated based on both theoretical insights and preliminary observations. The primary focus of this study is the design and implementation of a prototype reverse osmosis-based drinking water treatment system capable of processing river water into potable water that meets established quality standards. This stage ensures that the research objectives are clearly defined and aligned with practical challenges in water treatment.

The next stage involves system requirement analysis, which aims to identify the functional and technical specifications needed for the prototype. This includes determining key components such as pre-treatment units (filtration), RO membranes, pumps, and post-treatment units such as ultraviolet (UV) disinfection. Additionally, operational parameters such as pressure, flow rate, and feed water characteristics are analyzed to ensure optimal system performance.

Subsequently, the design and implementation phase is carried out. In this stage, the system is first designed conceptually and technically to ensure feasibility and effectiveness. The design process includes the preparation of system schematics, component selection, and configuration of the treatment process. Once the design is validated, the prototype is constructed and assembled according to the specified design. The implementation process aims to produce a functional system capable of treating river water into drinking water.

In parallel, a supply and demand analysis is conducted to estimate the required capacity of the system. This is achieved through survey-based data collection to assess community water needs. The results of this analysis are used to determine the production capacity and operational scale of the prototype system, ensuring that it is aligned with real-world demand conditions.

The final stage involves system testing and performance analysis. The prototype is tested using river water as the raw water source, and the treated water is analyzed based on physical, chemical, and microbiological parameters. The results are then compared with applicable drinking water quality standards, particularly those defined in national regulations. This stage also includes evaluating system efficiency, identifying operational challenges such as membrane fouling or pressure instability, and assessing overall system reliability.

3. DISCUSSION

a. System Design

The design of the reverse osmosis (RO)-based drinking water treatment system is developed to achieve high-quality potable water that complies with international and national standards. The system adopts an integrated multi-stage filtration approach consisting of pre-treatment, core-treatment, and post-treatment units. This configuration is essential to ensure optimal contaminant removal, system stability, and consistent water quality output, as in figure 2.

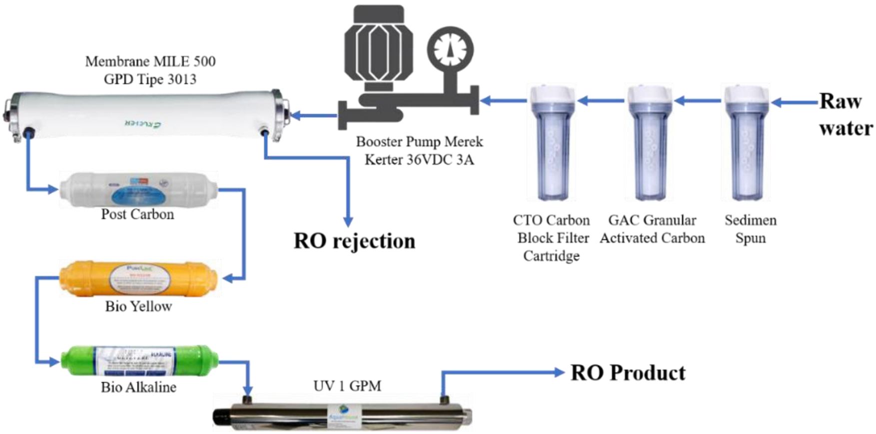

Figure 2. System block diagram

In the pre-treatment stage, three filtration units are employed, namely sediment filtration (5 µm), Granular Activated Carbon (GAC), and Carbon Block (CTO). The sediment filter serves as the first barrier to remove suspended solids such as sand, rust, and fine particles that contribute to turbidity. This stage is crucial in preventing clogging and fouling in subsequent filtration units, particularly the RO membrane. The GAC filter functions as an adsorption medium to remove chlorine, volatile organic compounds (VOCs), and odor-causing substances, while the CTO filter enhances chemical removal efficiency due to its higher density structure. The combination of these filters significantly improves feed water quality and protects the RO membrane from chemical degradation.

The core-treatment stage utilizes a reverse osmosis membrane (MILE 3013, 500 GPD), which serves as the primary purification unit. The RO process operates by applying high pressure (100–120 psi) using a booster pump (36 VDC, 3A) to force water through a semi-permeable membrane. This mechanism effectively removes dissolved solids, heavy metals, and microbial contaminants. The system is capable of achieving a Total Dissolved Solids (TDS) reduction of more than 95%, indicating high purification efficiency. The stable pressure provided by the booster pump is a critical factor in maintaining membrane performance and ensuring consistent production capacity.

Following the core-treatment, the post-treatment stage is implemented to enhance water quality from both health and sensory perspectives. The post carbon filter (T33) improves taste and odor, ensuring the water is more acceptable for consumption. The Bio Yellow cartridge reintroduces essential minerals such as calcium and magnesium, addressing the issue of mineral depletion commonly associated with RO-treated water. Additionally, the Bio Alkaline filter increases the pH level to a slightly alkaline range (7.5–8.5), which is considered beneficial for human health. The final stage employs an ultraviolet (UV) sterilizer (1 GPM) to eliminate any remaining microorganisms, providing an additional safety barrier against microbiological contamination, as in table 1.

Table 1. Technical specifications

Main Component	Technical Specification
System Capacity	500 GPD (± 1,900 L/day)
Pump Power Supply	36 VDC, 3 A (Kerter Booster Pump)
RO Membrane	MILE Type 3013, 500 GPD
Pre-treatment	5 µm Sediment Spun Filter, GAC, CTO
Post-treatment	Post Carbon, Bio Yellow (Mineral Filter), Bio Alkaline (pH Booster), UV 1 GPM
Water Output	TDS < 50 ppm, pH 7.5–8.5, free from bacteria and viruses
Operating Pressure	100–120 psi
Filter Lifespan	6–12 months (depending on raw water quality)

From a system integration perspective, the eight-stage configuration demonstrates a comprehensive approach to water treatment. Each stage performs a specific function that complements the others, resulting in a synergistic process. The pre-treatment ensures the longevity and efficiency of the RO membrane, the core-treatment provides the main purification process, and the post-treatment enhances water quality and safety. This layered design minimizes the risk of system failure and improves overall reliability.

The system capacity of 500 GPD (±1,900 liters per day) is suitable for small-scale or decentralized applications, such as institutional or community-level water supply. Operational parameters, including pressure, flow rate, and filter lifespan (6–12 months), indicate that the system is both technically feasible and practically implementable. Furthermore, the output water quality, characterized by low TDS (<50 ppm), balanced pH, and absence of pathogens, confirms that the design meets established drinking water standards.

b. Implementation

The implementation phase represents the realization of the previously designed eight-stage reverse osmosis (RO)-based drinking water treatment system. This stage involves the assembly, integration, and operation of all system components into a fully functional unit capable of producing potable water that complies with established quality standards.

The implementation process begins with the installation of the pre-treatment units, consisting of a sediment spun filter (5 µm), Granular Activated Carbon (GAC), and Carbon Block (CTO). These units are arranged sequentially to remove suspended solids, reduce turbidity, and eliminate chlorine and organic contaminants that may adversely affect membrane performance. The pre-treatment stage plays a critical role in protecting the RO membrane from fouling and chemical degradation, thereby extending its operational lifespan.

Following pre-treatment, a booster pump (36 VDC, 3A) is installed to maintain a stable operating pressure within the range of 100–120 psi. This pressure is essential to drive the reverse osmosis process effectively, ensuring optimal permeation through the semi-permeable membrane. The core treatment unit consists of an RO membrane (MILE 3013, 500 GPD), which is installed within a pressure vessel and connected through a series piping configuration. The system is designed to separate feed water into permeate (treated water) and concentrate (reject water), with the permeate directed to subsequent treatment stages.

The post-treatment stage is implemented to enhance both the safety and acceptability of the treated water. A post carbon filter (T33) is installed to improve taste and odor, followed by a mineralization unit (Bio Yellow cartridge) that reintroduces essential minerals such as calcium and magnesium. Subsequently, a Bio Alkaline cartridge is used to adjust the pH of the water to a slightly alkaline range (approximately 7.0–8.5), aligning with recommended drinking water conditions. The final stage incorporates a UV sterilizer (1 GPM), which provides disinfection by inactivating bacteria, viruses, and other pathogenic microorganisms through ultraviolet irradiation.

During the implementation process, system integrity tests are conducted to ensure proper installation and functionality. These tests include inspection of pipe connections, evaluation of potential leakage in filter housings, and preliminary flow rate measurements. Additionally, calibration of the booster pump and adjustment of flow rates are performed to ensure that the RO membrane operates under optimal conditions.

The system is then subjected to initial operational testing using river water as the raw water source. The treated water is evaluated based on key physical, chemical, and microbiological parameters to verify compliance with applicable drinking water standards. Observations also include a comparison between permeate and reject streams to assess separation efficiency and system performance.

Overall, the implementation phase successfully results in a fully integrated eight-stage RO system with a capacity of 500 GPD. The system demonstrates functional stability and readiness for further performance evaluation, providing a practical and scalable solution for decentralized drinking water treatment applications, as in figure 3.

Figure 3. Implementation

c. analysis

The analysis of water quality performance in this study focuses on evaluating the effectiveness of the treatment system in improving the characteristics of raw river water into potable water that complies with applicable standards. The raw water used in this study originates from the Musi River, which is characterized by fluctuating tidal conditions and significant contamination levels. Initial laboratory testing indicated that the raw water did not meet clean water standards, particularly in terms of turbidity, color, and iron (Fe) concentration, which exceeded permissible limits. These findings confirm the necessity of implementing a multi-stage treatment process to ensure safe water quality.

Following preliminary chemical treatment, the water quality showed substantial improvement, with all physical and chemical parameters meeting the required standards for clean water. Parameters such as Total Dissolved Solids (TDS), turbidity, color, and pH were significantly reduced to within acceptable limits. This indicates that the pre-treatment process plays a crucial role in stabilizing raw water quality before entering the advanced treatment stage. The reduction of chlorine residuals to near zero further demonstrates the effectiveness of the dechlorination process, which is essential to prevent damage to the RO membrane.

The performance of the reverse osmosis (RO) system was evaluated based on its ability to remove dissolved solids, hardness, alkalinity, and heavy metals. The results show a significant reduction in Total Hardness from 278.47 ppm $CaCO_3$ to 1.21 ppm $CaCO_3$, indicating a removal efficiency of more than 99%. Similarly, bicarbonate alkalinity decreased from 291.16 ppm to 13.86 ppm, reflecting the system's capability to reduce carbonate compounds that influence pH stability. Chloride concentration also decreased substantially from 84.60 ppm to 6.5 ppm, demonstrating effective ion separation by the RO membrane.

One of the most critical findings is the complete removal of iron (Fe), which decreased from 3.79 ppm in raw water to undetectable levels (0 ppm) after treatment. This highlights the high selectivity and efficiency of the RO membrane in removing heavy metals. Additionally, silica (SiO_2) content was reduced from 64 ppm to 2 ppm, further confirming the membrane's ability to remove inorganic compounds. The TDS value decreased from 29.5 ppm to 21.65 ppm, indicating that the treated water falls well below the maximum allowable limit for drinking water, thus ensuring high purity.

From a chemical stability perspective, the pH value remained relatively stable, with only a slight decrease from 7.35 to 7.10, which is still within the acceptable range (6.5–8.5). This stability suggests that the post-treatment processes, including mineralization and alkaline filtration, effectively maintain the balance of water chemistry after RO filtration.

Overall, the analysis demonstrates that the integration of chemical pre-treatment and RO technology significantly enhances water quality across all key parameters. The system is highly effective in removing both physical and chemical contaminants, including dissolved ions, hardness, heavy metals, and organic compounds. The resulting water quality meets national drinking water standards, confirming that the proposed system is technically feasible and reliable for producing safe drinking water.

Furthermore, the comparison between permeate and reject streams indicates efficient separation performance, with contaminants effectively concentrated in the reject stream while producing high-quality permeate. This validates the operational effectiveness of the system and supports its application in decentralized water treatment systems, particularly for river water sources with variable quality.

4. CONCLUSION

This study has successfully designed, implemented, and evaluated a prototype drinking water treatment system based on reverse osmosis (RO) technology with a capacity of 500 GPD. The system integrates an eight-stage treatment process consisting of pre-treatment, core-treatment, and post-treatment units, enabling comprehensive removal of physical, chemical, and microbiological contaminants. The results show that raw water from the Musi River initially did not meet clean water standards, particularly in terms of turbidity, color, and iron content. However, after undergoing chemical pre-treatment and RO-based processing, the treated water met all required drinking water quality standards. Significant reductions were observed in key parameters such as total hardness, alkalinity, chloride, silica, and total dissolved solids (TDS), along with the complete removal of iron. The RO system demonstrated high effectiveness in separating dissolved ions and contaminants while maintaining stable pH conditions within acceptable limits. The addition of post-treatment units, including mineralization, pH adjustment, and UV sterilization, further improved water quality and ensured microbiological safety. Overall, the developed system is technically feasible, efficient, and reliable for producing high-quality drinking water from river sources. This prototype shows strong potential for application in decentralized water treatment systems, particularly in areas with limited access to safe drinking water.

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