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Design of a Reverse Osmosis–Based Seawater Desalination System Utilizing Coconut Shell

Mutia Amyranti [*], Bambang Andri Yoga, Ratih Kurniasari, Ismi Nurlatifah, Lily Arlianti, Siti Maftukhah, Dine Agustine

Department of Chemical Engineering, Faculty of Engineering, Universitas Islam Syekh Yusuf, Indonesia
*Email (corresponding author): mutiaamyranti@unis.ac.id

Abstract. *Freshwater scarcity remains a critical challenge in small island regions, particularly in archipelagic countries such as Indonesia, where seawater is abundant but access to clean freshwater is limited. Tunda Island, located in Serang Regency, Banten Province, exemplifies this condition, as local communities primarily depend on rainwater harvesting and shallow groundwater sources to meet daily water demands. This study aims to evaluate a modified reverse osmosis (RO) desalination system integrated with coconut shell–based activated carbon as an adsorptive pretreatment medium for seawater desalination. The coconut shell adsorbent was employed to enhance pretreatment efficiency and improve the overall performance of the RO system. Seawater samples collected from Tunda Island were processed through the integrated system, and the quality of the treated water was evaluated according to the Indonesian Ministry of Health standards. Key parameters analyzed included Chemical Oxygen Demand (COD), Biological Oxygen Demand (BOD), Total Dissolved Solids (TDS), Total Suspended Solids (TSS), pH, color, and temperature. The results demonstrated that the treated water achieved COD of 120.10 mg/L, BOD of 10.5 mg/L, TSS of 3.76 mg/L, TDS of 117.245 ppm, pH of 7.30, clear color, and a temperature of 27°C, indicating compliance with applicable water quality standards. These findings confirm that the integration of coconut shell–based activated carbon with reverse osmosis effectively improves desalination performance and produces freshwater suitable for domestic use.*

Keywords: *Seawater Desalination; Reverse Osmosis; Coconut Shell Adsorbent; Water Quality; Small Islands*

1. Introduction

Indonesia has been internationally recognized as an archipelagic nation since the adoption of the United Nations Convention on the Law of the Sea (UNCLOS) in 1957. According to statistical data from the Central Bureau of Statistics (BPS), approximately 62% of Indonesia's total territory consists of marine waters, encompassing more than 17,500 islands and a coastline extending over 81,000 km. Despite this vast marine dominance, many small islands continue to experience severe limitations in accessing clean freshwater, making water scarcity a persistent and unresolved challenge (1).

This condition is particularly evident on Tunda Island, administratively located in Serang Regency, Banten Province (2). With an area of approximately 300 hectares and a population of around 4,500 inhabitants, Tunda Island is surrounded by abundant seawater yet lacks sustainable freshwater resources (3). Field observations and interviews with local authorities indicate that most residents rely on shallow groundwater wells and rainwater harvesting stored in tanks to meet daily domestic needs such as cooking and washing. As

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population growth and socio-economic activities increase, the pressure on limited freshwater sources intensifies, highlighting the urgent need for alternative and sustainable water supply solutions (4).

Seawater desalination has emerged as a strategic approach to address freshwater scarcity in coastal and island regions. Conventional desalination technologies include thermal-based processes such as distillation and multiple-effect evaporation, while membrane-based technologies offer higher separation efficiency with lower energy requirements(5). Among these methods, reverse osmosis (RO) has become the most widely implemented desalination technology due to its high salt rejection capability, modular system configuration, and relatively low operational costs (6). RO systems operate by applying pressure greater than the osmotic pressure of seawater, forcing water molecules through a semi-permeable membrane while retaining dissolved salts and impurities.

Various membrane-based desalination technologies—including reverse osmosis, electrodialysis reversal (EDR), nanofiltration (NF), and membrane distillation (MD)—have been extensively investigated (7). Nevertheless, RO remains the dominant technology, capable of achieving salt rejection rates exceeding 99% and producing permeate with total dissolved solids (TDS) levels below 300 ppm in single-stage operation (8). Despite these advantages, membrane fouling caused by organic matter and suspended solids remains a major technical limitation, leading to reduced membrane performance, increased energy consumption, and higher operational costs. Consequently, the development of effective and sustainable pretreatment strategies is critical for improving RO system reliability and longevity (9).

Adsorption-based pretreatment using activated carbon has been widely reported as an effective method for reducing organic contaminants and mitigating fouling potential in desalination systems (10). Recent studies have explored various biomass-derived activated carbons, such as bamboo charcoal, which demonstrated salt reduction efficiencies of up to 81.55%, although further optimization was required to meet drinking water standards (11). Among biomass-based materials, coconut shell–derived activated carbon has gained increasing attention due to its high carbon content, large specific surface area, strong adsorption capacity, low cost, and wide availability in tropical and coastal regions (12). Activated carbon produced from coconut shell has been reported to achieve adsorption capacities exceeding 1,240 mg/g with surface areas greater than 2,300 m^2/g, indicating its strong potential for water treatment applications (6).

Despite extensive studies on reverse osmosis and activated carbon separately, limited research has focused on the integration of coconut shell–based activated carbon as an adsorptive pretreatment material within RO desalination systems, particularly for small island applications. Moreover, the utilization of locally available biomass waste as a functional component in desalination systems remains underexplored from both technical and sustainability perspectives.

The objectives of this study are as follows, to evaluate the quality of freshwater produced by a reverse osmosis desalination system integrated with coconut shell–based activated carbon, based on clean water quality parameters. To assess the suitability and effectiveness of coconut shell–based activated carbon as an adsorbent medium in supporting reverse osmosis desalination for meeting freshwater needs in small island communities, particularly on Tunda Island.

Therefore, this study proposes a modified reverse osmosis desalination system incorporating coconut shell–based activated carbon as an adsorbent medium to enhance pretreatment performance and overall desalination efficiency. The system is evaluated using seawater samples from Tunda Island, with treated water quality assessed against national regulatory standards. By integrating membrane-based desalination with locally sourced biomass-derived adsorbents, this research aims to contribute to the development of sustainable, low-cost, and environmentally friendly desalination technologies for small island and coastal communities

2. Methods

2.1 Preparation of Coconut Shell–Based Activated Carbon

Coconut shells used in this study were collected from local communities around Tunda Island, Indonesia. The raw coconut shells were first washed thoroughly with running water to remove surface impurities and adhering contaminants. The cleaned shells were then sun-dried until a constant weight was achieved. The dried coconut shells were carbonized in a muffle furnace at a temperature range of 200–300°C for 60 minutes, resulting in coconut shell charcoal. The produced charcoal was subsequently ground and sieved using a 100-mesh sieve to obtain uniform particle size. Chemical activation was performed using potassium hydroxide (KOH) as the activating agent. A fixed amount of charcoal was immersed in 100 mL of 2 M KOH solution and allowed to soak for 24 hours to ensure sufficient impregnation. After activation, the material was thoroughly washed with distilled water until a neutral pH was achieved in order to remove residual KOH. The activated carbon was then dried in an oven to obtain the final coconut shell–based activated carbon product, following the method reported by (13). The selection of KOH as an activating agent was based on its ability to generate well-developed pore structures and enhance adsorption properties. During chemical activation, KOH reacts with carbon atoms, promoting the formation of micro-, meso-, and external pores (14). This process effectively removes impurities formed during carbonization and significantly increases surface area and pore volume. Previous studies have reported that KOH-activated carbon exhibits superior adsorption capacity compared to NaOH-activated carbon, with surface area values reaching up to 72.413 m^2/mg, while NaOH activation resulted in significantly lower surface area values (approximately 420.2 m^2/g) (15). Activated carbon is inherently hygroscopic, allowing it to readily absorb moisture from the surrounding air. A low moisture content is desirable, as excessive water content can reduce adsorption efficiency for both gases and liquids. In this study, the use of KOH also served as a dehydrating agent by binding water molecules within the raw material, thereby enlarging pore structures and increasing effective adsorption surface area. This characteristic makes KOH-activated coconut shell carbon particularly suitable for use as an adsorbent in water treatment applications (16)

2.2 Reverse Osmosis Desalination Process

The prepared coconut shell–based activated carbon was employed as an adsorptive pretreatment medium in a modified reverse osmosis desalination system. Seawater samples were collected from the coastal waters of Tunda Island, specifically near the local fishing harbor. Prior to entering the RO membrane unit, seawater was passed through a filtration column packed with the activated carbon to reduce organic contaminants and suspended solids, thereby minimizing membrane fouling potential (17).

Following pretreatment, the filtered seawater was processed through the reverse osmosis system operated at a pressure exceeding the osmotic pressure of seawater. The RO membrane selectively allowed water molecules to pass through while retaining dissolved salts and impurities. The resulting permeate was collected as treated freshwater, while the concentrate stream was discharged as brine.

The quality of the treated water was subsequently analyzed based on clean water quality standards, including Chemical Oxygen Demand (COD), Biological Oxygen Demand (BOD), Total Dissolved Solids (TDS), Total Suspended Solids (TSS), pH, color, and temperature, to evaluate the effectiveness of the integrated adsorption–RO system.

3. Results and Discussion

This section presents and discusses the results obtained from the seawater desalination experiments using the modified reverse osmosis system integrated with coconut shell–based activated carbon.

3.1 Modification of the Reverse Osmosis Method

In this study, the reverse osmosis (RO) desalination method was modified by integrating KOH-activated coconut shell–based activated carbon as part of the pretreatment system. This modification was motivated by the persistent freshwater scarcity experienced by the residents of Tunda Island, where access to clean water remains limited despite the abundance of seawater (18). Membrane-based desalination was selected as the core technology due to its proven effectiveness in salt separation and its suitability for decentralized applications in island environments.

Reverse osmosis membranes are generally defined as thin semi-permeable layers that function as selective barriers, allowing water molecules to pass through while retaining dissolved salts and other contaminants. Previous studies have reported that RO membranes are capable of removing up to 99.4–99.6% of dissolved salts, making them one of the most efficient desalination technologies currently available (19). However, membrane fouling caused by organic matter, suspended solids, and inorganic impurities remains a major operational challenge, particularly when treating raw seawater without adequate pretreatment. To address this limitation, the RO system in this study was modified by incorporating a dual-pipe pretreatment and membrane configuration. The system consisted of two large pipes with a diameter of 10 inches. The first pipe functioned as a pretreatment adsorption column, packed with a combination of KOH-activated coconut shell carbon, zeolite, silica sand, and gravel (20). This multilayer adsorptive media was designed to remove organic and inorganic contaminants through adsorption and physical filtration mechanisms. The activated carbon played a dominant role in adsorbing dissolved organic compounds, including potentially toxic substances, while zeolite and silica sand contributed to the removal of suspended solids and fine particulates (4). The second pipe housed the RO membrane, which served as the core separation unit of the system. Following pretreatment, the filtered seawater entered the RO membrane module, where desalination occurred through pressure-driven membrane separation. The presence of the adsorptive pretreatment stage significantly reduced the contaminant load entering the RO membrane, thereby enhancing membrane performance and reducing fouling potential (21).

The effectiveness of this modified RO system was evaluated based on water quality parameters regulated by Indonesian drinking and clean water standards (22). According to the Decree of the Indonesian Ministry of Health No. 907/Menkes/SK/VII/2002 and the updated Regulation of the Ministry of Health No. 2 of 2023, clean water is considered suitable for use if it has a pH between 6.5 and 8.5, is colorless, odorless, and meets physicochemical quality requirements (23). Therefore, comprehensive water quality testing was conducted to ensure compliance with these standards.

The results indicate that the modified RO system incorporating coconut shell–based activated carbon as an adsorbent medium successfully produced water that met the required quality criteria. This demonstrates that the integration of locally sourced biomass-derived adsorbents with membrane-based desalination technology can enhance system performance while maintaining compliance with regulatory standards. From an engineering perspective, this modification represents a practical and sustainable approach to improving RO desalination systems for small island applications. By utilizing readily available coconut shell waste, the system not only improves desalination efficiency but also aligns with the principles of green engineering and circular economy, making it particularly suitable for coastal and island communities such as Tunda Island .

3.1.1 Reverse Osmosis Process Operation

Seawater samples were first collected and stored in a main feed container. The water was then conveyed through a 1-inch PVC pipeline into the first treatment column, which functioned as the pretreatment unit. This column contained multiple filtration and adsorption media arranged in layers. Gravel was used to provide primary filtration and support oxygen aeration, while silica sand was employed to retain suspended sediments. Zeolite served as a filtration medium for removing fine solid particles. KOH-activated coconut shell carbon (20% KOH) acted as the main adsorbent, responsible for reducing dissolved organic and inorganic contaminants during the pretreatment stage. Following pretreatment, the water was directed into the second column containing the reverse osmosis (RO) membrane, which served as the core desalination unit. In this stage, seawater was subjected to membrane separation, allowing water molecules to pass through while retaining dissolved salts and impurities, thereby producing freshwater. The permeate was subsequently passed through a cartridge filter to remove residual fine particles according to the filter mesh size before final collection.

3.1.2 Seawater Desalination Process

Activated carbon filtration is one of the commonly applied methods in water treatment and desalination, particularly for reducing salt-related contaminants and organic pollutants. Previous studies have reported that activated carbon–based filtration provides a cost-effective approach for improving water quality prior to membrane desalination. In this study, a combination of zeolite, gravel, silica sand, and coconut shell–based activated carbon was employed as filtration media to enhance pretreatment efficiency. These materials are readily available and economically feasible, making them suitable for desalination applications in small island environments (9). Figure 1 illustrates these stages.

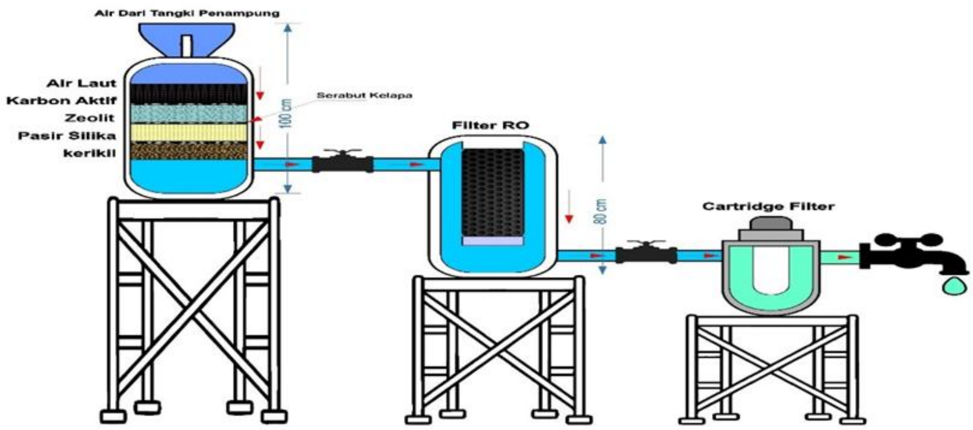

Figure 1. Seawater Desalination

3.2 Performance Analysis of the Reverse Osmosis System

The effectiveness of the reverse osmosis (RO) system was confirmed by the reduction of organic pollution indicators. The treated water showed COD and BOD values of 120.10 mg/L and 10.5 mg/L, respectively, which complied with clean water quality standards, indicating that the RO process combined with coconut shell–based activated carbon effectively reduced organic contaminants. A significant decrease in Total Dissolved Solids (TDS) was observed after RO treatment. TDS values were reduced to 117.245 mg/L, well below the maximum allowable limit of 1000 mg/L, demonstrating the high salt rejection efficiency of the RO membrane and confirming its effectiveness in seawater desalination. The RO system achieved a low TSS value of 3.76 mg/L, indicating efficient removal of suspended particles. This result confirms the role of pretreatment and membrane filtration in minimizing turbidity and protecting membrane performance. The pH of the treated water was 7.30, falling within the acceptable range of 6.5–8.5. This indicates that the RO desalination process did not significantly alter the acidity or alkalinity of the water, ensuring its suitability for domestic use. The temperature of the treated water was recorded at 27°C, which is within the normal range specified by water quality regulations. This suggests that the RO process did not introduce thermal stress or adverse temperature changes. Color analysis showed a value of 0 TCU, indicating that the treated water was clear and free from visible contaminants. This confirms that the integrated adsorption–RO system effectively removed color-causing substances and met aesthetic water quality standards.

Based on all evaluated parameters and in accordance with PERMENKES No. 2 of 2023, the reverse osmosis system integrated with coconut shell–based activated carbon successfully produced freshwater that met clean water quality standards (22,23). These results demonstrate the reliability and effectiveness of the modified RO system for desalination applications in small island environments such as Tunda Island. The results can be seen in Table 1.

Table 1. Water Sample Examination Results

No.	Parameter	Unit	Quality Standard	Seawater Sample	RO-Treated Water Sample
1	COD (Chemical Oxygen Demand)	mg/L	350	200.16	120.10
2	BOD (Biological Oxygen Demand)	mg/L	100	105.77	10.5
3	TSS (Total Suspended Solids)	mg/L	250	5.25	3.76
4	TDS (Total Dissolved Solids)	ppm	>1000	283.165	117.245
5	pH	–	6.0 – 9.0	7.80	7.30
6	Color	–	Colorless	Clear	Clear / Non-turbid
7	Temperature	°C	Ambient temperature ± 30°C	29°C	27°C

Conclusions

The modified reverse osmosis system integrated with coconut shell–based activated carbon successfully produced freshwater that met clean water quality standards. The RO-treated water achieved COD of 120.10 mg/L, BOD of 10.5 mg/L, TSS of 3.76 mg/L, TDS of 117.245 ppm, pH of 7.30, temperature of 27°C, and color of 0 TCU, all within the acceptable limits specified by PERMENKES No. 2 of 2023. These results confirm the effectiveness of the adsorption-assisted RO system for seawater desalination in small island environments

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Conflicts of Interest

The authors declare no conflict of interest

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