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Puresense RO system: a decentralized brackish water treatment framework for coastal communities

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ABSTRACT

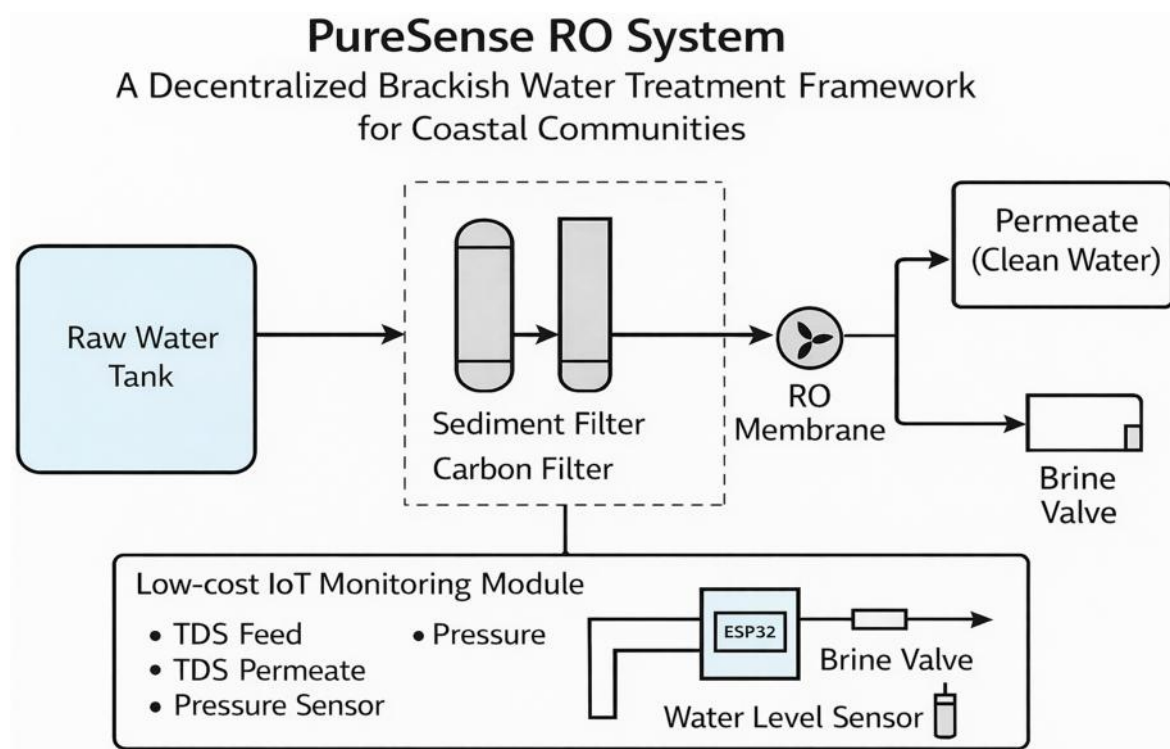
Indonesia has deployed numerous government-funded brackish water reverse osmosis (BWRO) and seawater reverse osmosis (SWRO) installations in coastal regions; however, many units fail to operate sustainably due to limited technical capacity, complex maintenance requirements, and the absence of reliable sensing and monitoring systems. Addressing this operational gap, this study develops and evaluates a low-complexity decentralized BWRO–SWRO system equipped with a simplified IoT-based monitoring module designed for stable operation in remote coastal settings. The prototype integrates STM32 control, ADS1115 high-resolution analog acquisition, and ESP-07 telemetry to monitor TDS, pH, temperature, and pressure with minimal sensor load. Testing was conducted using four feedwater sources with different salinity profiles. Results show permeate TDS consistently within 15–45 mg/L, rejection rates of 96–98%, operational pressure stability at 110–120 psi, and recovery ranging from 9–16% depending on feed characteristics. These findings demonstrate that a decentralized RO configuration with simplified instrumentation can deliver high-quality permeate while reducing failure points, operator burden, and maintenance complexity. This work provides a practical engineering approach to improving the reliability and sustainability of small-scale desalination systems in coastal communities.

Key words: brackish water, coastal communities, decentralized desalination, IoT monitoring, reverse osmosis, seawater intrusion, small-scale water treatment

HIGHLIGHTS

- Proposes a decentralized hybrid brackish water reverse osmosis and seawater reverse osmosis (SWRO) concept for brackish saline coastal conditions.
- Uses a low-complexity IoT module with four sensors (total dissolved solids, pH, temperature, and pressure).
- Achieves 96–98% rejection and 15–45 mg/L permeate across variable salinity.
- Improves reliability through simplified instrumentation and reduced maintenance.
- Delivers a field-ready, scalable reverse osmosis framework aligned with WPT principles.

GRAPHICAL ABSTRACT



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INTRODUCTION

Access to safe and reliable freshwater remains a persistent issue in many coastal regions, particularly in developing countries that rely heavily on groundwater, rainwater harvesting, or government-run desalination plants. In Indonesia, more than 12,000 coastal villages still face varying degrees of water stress, with only around 66% having access to basic clean-water services (Arfah 2019). Conventional solutions such as centralized sea water reverse osmosis (SWRO) and brackish water reverse osmosis (BWRO) plants have been installed in several locations, including the Kepulauan Seribu area of Jakarta. However, these systems are often challenged by high operational costs, limited technical capacity, and logistical constraints in maintenance and monitoring (Aldila 2019).

Recent studies on RO-based desalination highlight improvements in membrane performance, fouling control, and energy efficiency for brackish water treatment (Gupta & Patel 2020; Al-Sarkhi *et al.* 2021). Other research has explored hybrid RO configurations that combine SWRO and BWRO characteristics to adapt to varying feed-water salinity (Utama 2022). Several works have also proposed techniques for enhancing operational reliability through real-time monitoring of RO membranes (Salman *et al.* 2019). Although these contributions demonstrate significant advancements, existing systems remain largely centralized, technically demanding, and not designed to support independent operation by small coastal communities or households.

A key gap identified in the current literature is the absence of decentralized RO frameworks tailored for small-scale brackish water treatment in remote coastal settings. Most RO implementations still depend on centralized infrastructure, professional technicians, and on-site monitoring – factors that limit sustainability in distributed island regions. Furthermore, studies rarely address configurations that allow communities to operate and maintain their own systems with minimal dependence on government-run facilities, despite evidence that decentralized water systems can improve resilience and accessibility in coastal environments (Rahmawati & Kim 2021).

To address this gap, this study proposes the puresense reverse osmosis (PSRO) concept, introduced as a decentralized brackish water treatment framework for coastal communities. The framework incorporates a tailored RO configuration designed specifically for brackish groundwater conditions commonly found in Indonesian coastal areas, while enabling more flexible operation and potential remote monitoring without requiring complex centralized infrastructure. This work aims to evaluate the feasibility, performance characteristics, and

operational considerations of the PSRO framework as an alternative small-scale solution that supports community-level water independence.

Although recent RO studies have expanded knowledge on membrane efficiency, hybrid configurations, and monitoring strategies, these advances remain oriented toward centralized facilities and do not fully consider the practical constraints of small coastal communities that rely on brackish groundwater with highly variable quality. Within this context, there is an opportunity to explore a configuration that maintains essential RO performance while simplifying operation and reducing monitoring complexity. Building on this space, the present study introduces the PSRO framework, a streamlined hybrid configuration equipped with selective monitoring points and designed to support community-scale operation. The evaluation presented here offers an initial demonstration of how PSRO can align technical performance with the usability requirements of coastal settings.

The main contribution of this study lies in the integration of a simplified hydraulic configuration with a minimal yet functionally effective monitoring strategy. Unlike conventional decentralized BWRO systems that rely on complex instrumentation and intensive operational control, the proposed PSRO system emphasizes selective monitoring-point placement, simplified hydraulic design, and operational robustness suitable for remote and resource-limited coastal communities. The novelty of this work is therefore not in the membrane technology itself, but in the integration of system design, monitoring strategy, and operational simplicity into a unified decentralized treatment framework.

METHODS AND MATERIALS

This study employed an experimental and design-based engineering approach to develop and evaluate the PSRO framework as a decentralized brackish water treatment solution for small coastal communities. The methodology consisted of four stages:

- (1) feedwater characterization,
- (2) PSRO system design,
- (3) prototype development and controlled testing, and
- (4) performance evaluation using RO quality indicators and operational stability metrics ([Ahmed et al. 2024](#); [Fu et al. 2024](#)).

All sensors were factory-calibrated prior to use, and manufacturer-specified accuracy ranges were considered sufficient for performance evaluation.

Feedwater characterization and problem identification

Brackish groundwater samples were collected from a coastal area in Jakarta to determine baseline water quality. Standard parameters were measured following APHA guidelines, including total dissolved solids (TDS), electrical conductivity (EC), pH, turbidity, and temperature.

These values were used to identify salinity levels, fouling potential, and the appropriate RO membrane class for brackish water, following the characterization approach reported by [Ahmed et al. \(2024\)](#).

Observations from existing BWRO/SWRO installations, particularly logistical and maintenance constraints reported in previous studies, were incorporated to define system requirements for a decentralized RO configuration ([Fu et al. 2024](#)).

PSRO configuration design

The PSRO framework integrates operational attributes of BWRO and SWRO but is tailored for small-scale community use. The design process included:

- *Membrane selection*: brackish water RO membrane suitable for 1,500–3,000 ppm feedwater ([Ahmed et al. 2024](#)).
- *Pretreatment*: sediment filter, activated-carbon filter, and optional antiscalant dosing.
- *Hybrid hydraulic layout*: combining low-pressure BWRO characteristics with simplified stability components adapted from SWRO circuits ([Fu et al. 2024](#)).
- *‘PureSense monitoring points’*: feed TDS, permeate TDS, pump pressure, flow rate, and raw-water tank level – selected to balance diagnostic usefulness with low system complexity.

A schematic block diagram ([Figure 1](#)) illustrates the PSRO flow sequence from raw-water intake through pretreatment, membrane module, and permeate collection.

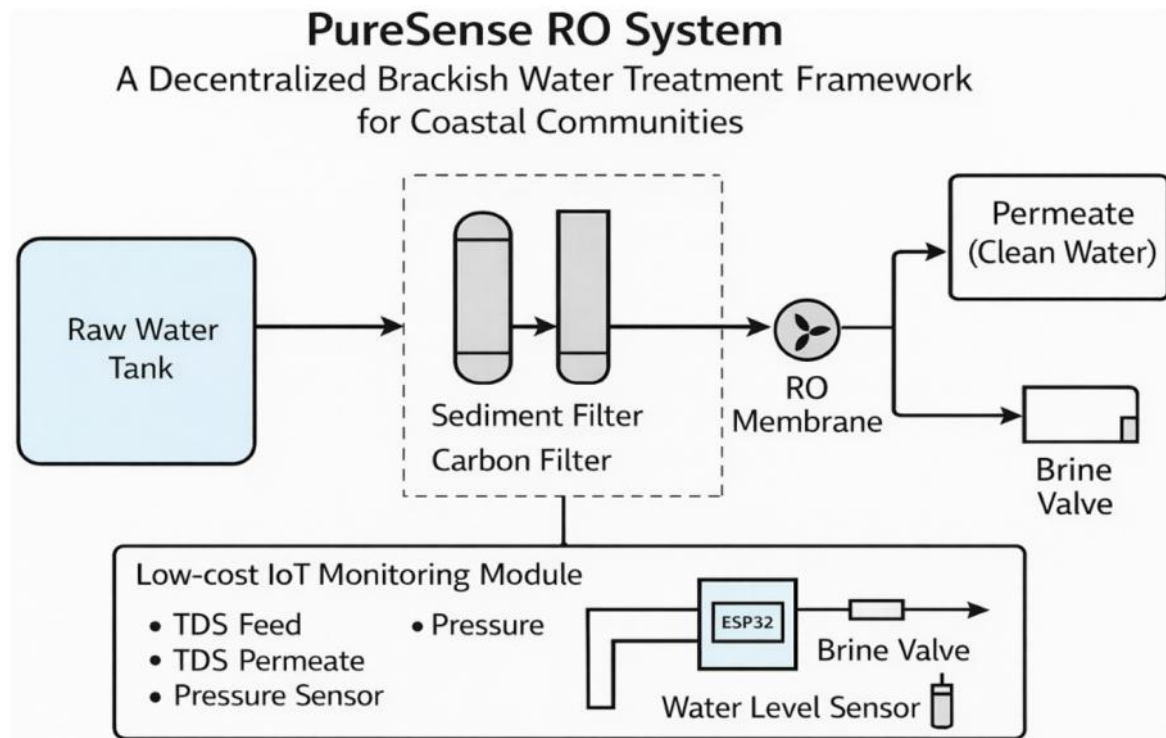


Figure 1 | Process-flow diagram of the PSRO system, showing the hydraulic configuration and sensor integration for decentralized brackish water purification.

Prototype assembly and testing procedure

A laboratory-scale prototype was developed to verify the operational feasibility of the PSRO configuration. The system included:

- raw water storage tank,
- multistage pretreatment unit,
- high-pressure pump,
- brackish water RO membrane,
- concentrate discharge valve, and
- permeate collection tank.

A low-cost IoT monitoring module based on ESP32 was integrated where applicable.

Testing protocol:

1. System flushing
Prefilters and membranes were cleaned and stabilized before testing.
2. Initial operating condition setup
 - Feed pressure set between 8 and 15 bar, depending on salinity.
 - Flow rate and pressure were monitored throughout.
3. Steady-state operation
System operated for a fixed period (e.g., 60–90 min per run).
4. Sample collection
Water samples were collected at:
 - feedwater.
 - permeate.
 - brine.
5. Parameter measurement
 - TDS reduction percentage.
 - permeate flow rate (L/h).

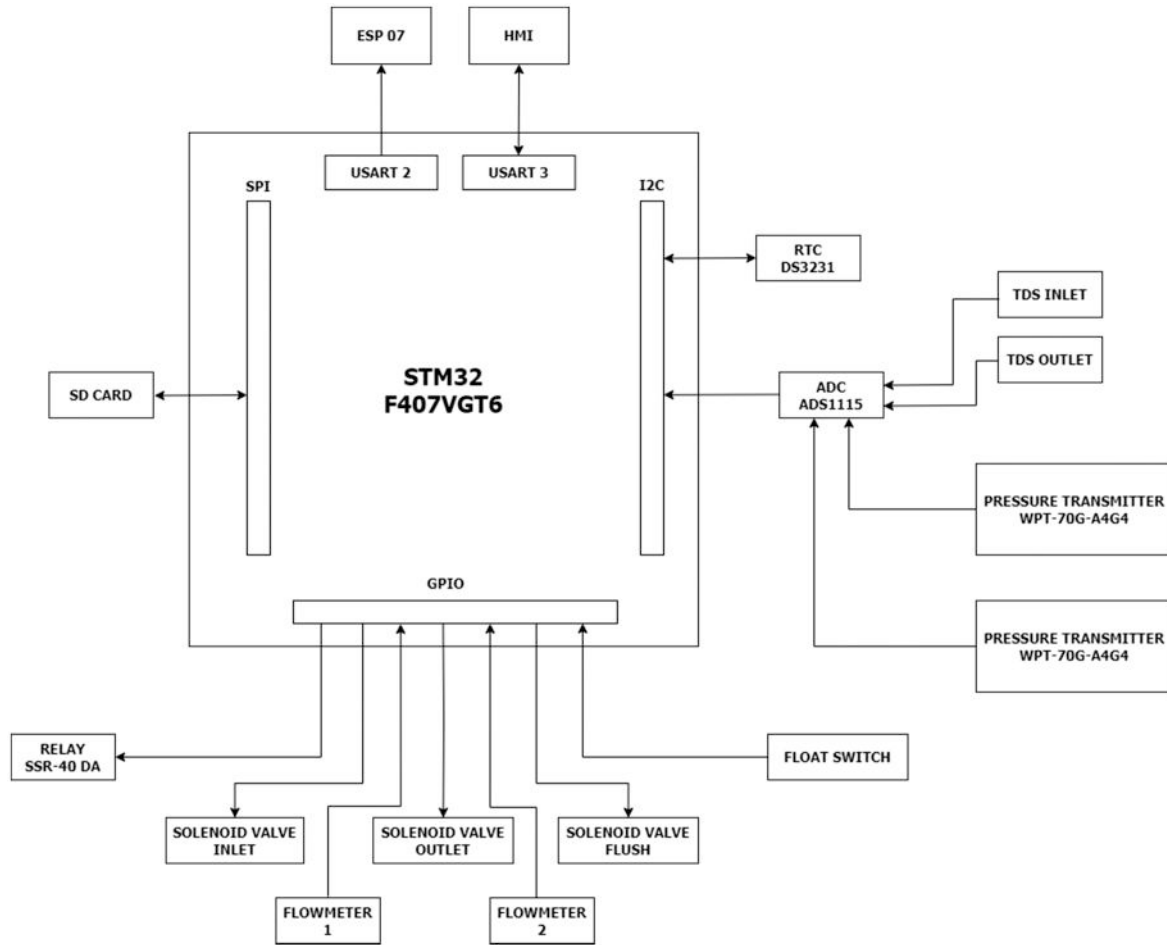


Figure 2 | The complete control-system block diagram, showing the interaction between sensing modules, signal-conditioning units, actuators, and the central controller.

- recovery ratio (%).
- stabilization time.
- pressure drop across the membrane.

Performance evaluation

The prototype was tested under laboratory and limited field conditions to assess both water quality and operational stability:

- Water quality assessment: TDS, EC, pH, turbidity, and temperature were measured at regular intervals.
- Rejection rate: calculated to evaluate membrane performance (Aladwani *et al.* 2021; Tayeh 2024):

$$\text{Rejection (\%)} = \frac{\text{TDS feed} - \text{TDS permeate}}{\text{TDS feed}} \times 100 \quad (1)$$

The rejection rate was calculated using Equation (1).

- Operational monitoring: pressure, flow, and tank level data were continuously recorded to detect changes or anomalies in system operation.
- Recovery rate: fraction of feed water converted to permeate (Aladwani *et al.* 2021):

$$\text{Recovery (\%)} = \frac{\text{Volume of permeate}}{\text{Volume of feed}} \times 100 \quad (2)$$

The recovery rate was calculated using Equation (2).

- User-friendliness: system operation was tested by nontechnical users to assess ease of use, monitoring, and maintenance.

RESULTS AND DISCUSSION

System architecture of the PSRO prototype

The PSRO was successfully assembled as a small-scale brackish water treatment unit designed for decentralized operation. The prototype integrates three core subsystems: (1) a multistage pretreatment module, (2) a brackish water RO membrane unit, and (3) a simplified monitoring block that includes TDS, pressure, and water-level sensing.

The process flow illustrated in Figure 1 begins at the raw-water storage tank, where brackish groundwater is first stabilized before entering the multistage pretreatment unit. Sediment and carbon filtration remove particulates and organic matter to reduce fouling potential prior to pressurization (Abushawish *et al.* 2023). The conditioned feedwater is then driven by a high-pressure pump into the brackish water RO membrane, where permeate and concentrate streams are separated (Shannon *et al.* 2008). A concentrate-control valve is used to maintain stable operating pressure and regulate recovery, adopting a stability mechanism typically found in small SWRO units (Tayeh *et al.* 2024). Permeate is routed into a collection tank for household or community use, while brine is discharged through a controlled reject line. Sensor nodes positioned at the feed line, membrane outlet, and storage tank, measuring TDS, pressure, flow rate, and water level, enable system monitoring through an ESP32-based module (Anastasopoulos *et al.* 2021). This configuration maintains low operational complexity while supporting decentralized use without onsite technical supervision.

Hardware configuration

Unlike the hydraulic configuration described in Section 4.1, which focuses on the physical water-treatment path, the PSRO system also incorporates an embedded electronic control architecture responsible for monitoring, regulation, and operational safety (Anastasopoulos *et al.* 2021). This control subsystem is built around an STM32 F407VGT6 microcontroller, which serves as the central processing unit for sensor acquisition, actuator control, and optional wireless communication (Ray 2018).

The STM32 receives input from multiple sensors positioned across the PSRO system, including:

- TDS sensors (inlet and permeate) for monitoring salinity reduction performance (Ho *et al.* 2022; Murugan *et al.* 2023; Peregrine IoT 2024).
- Pressure transmitters (WPT-70G-A4G4) installed at the feed and post-pump lines to detect hydraulic imbalance or membrane fouling.
- Dual flowmeters for measuring inlet and permeate flow rate (GE Osmonics 2003; Ho *et al.* 2022).
- Float switch for raw-water tank level control (Agussationo *et al.* 2024).
- ADC module (ADS1115) for high-resolution analog signal acquisition (DFRobot/ADS1115 module documentation, 2024; Beddows & Mallon 2018).
- RTC module (DS3231) for timestamping water-quality logs (Beddows & Mallon 2018).

Actuator components connected to the STM32 include:

- Solenoid valves (inlet, outlet, and membrane flush) for regulating the flow path.
- Solid-state relay (SSR-40DA) for pump activation and electrical isolation.

The control board is additionally supported by

- An ESP-07 wireless module for optional remote monitoring or data transmission.
- An HMI interface for local status display and manual override.
- An SD-card interface for on-device water-quality and performance logging.

This modular electronic architecture enables the PSRO system to maintain stable operation under varying feedwater conditions while reducing the need for direct onsite supervision – an essential requirement for decentralized implementation in coastal communities.

Prototype design and physical assembly

The PureSense RO prototype was assembled as a compact, field-deployable purification unit integrating all hydraulic and control components into a single functional frame. The physical design prioritizes accessibility, modular replacement, and community-level operability without requiring specialized technical skills.

Figure 3 shows the assembled prototype layout, including the raw-water inlet, multi-stage pre-filters (sediment, granular activated carbon, and CTO), booster pump, brackish water RO membrane housings, concentrate and permeate outlets, and the instrumentation points used during system testing (Wijaya *et al.* 2025). A pressure transmitter is installed at the membrane feed line to ensure stable operating pressure during recovery adjustment, while a flowmeter is positioned at the inlet to support flow monitoring during flushing and recovery optimization.

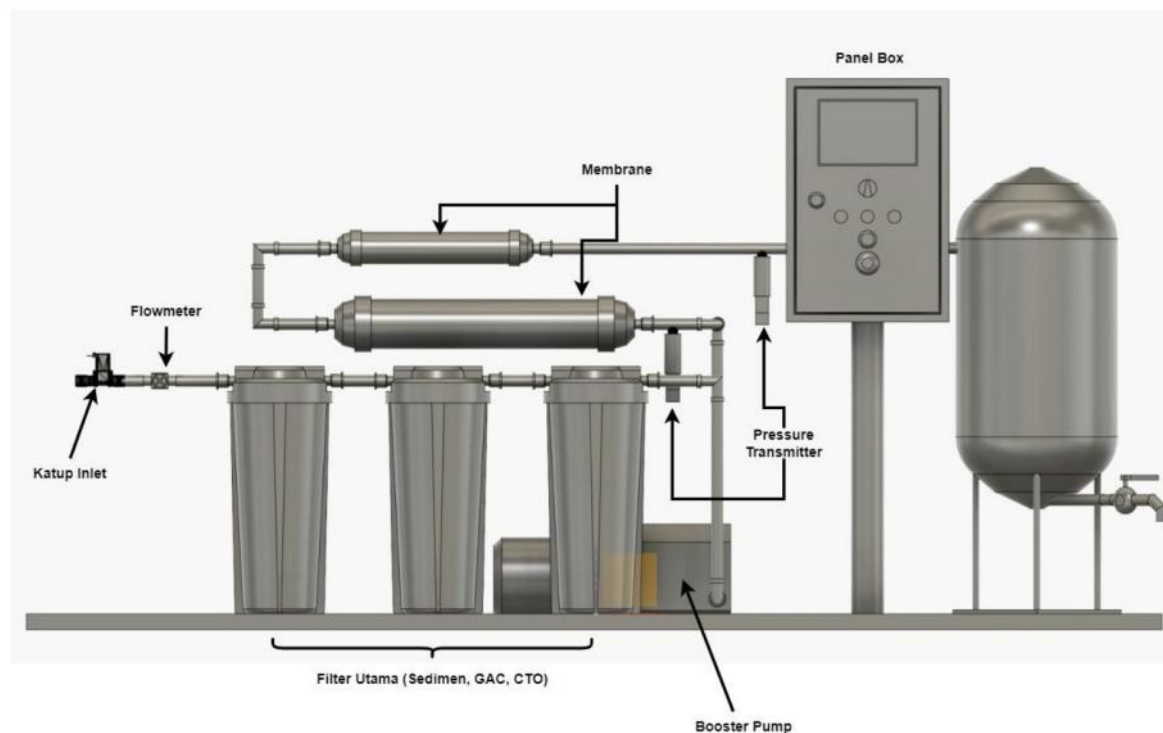


Figure 3 | Physical prototype of the puresense RO system, showing the integrated arrangement of pre-filters, RO membrane modules, booster pump, pressure transmitter, and control panel.

The control panel mounted as a separate enclosure contains the microcontroller, power circuitry, relay switches, interface buttons, and a compact display module. This separation allows users to safely interact with the control elements while keeping hydraulic components protected from splashing and unintended manual interference. The structural layout reflects the intended deployment model for small coastal communities, where routine tasks such as cartridge replacement, flushing, and membrane inspection can be completed quickly by nontechnical users.

In addition to the physical control panel, the prototype is complemented by a lightweight monitoring and control interface accessible through a web dashboard and mobile application. This software layer allows users to check filtration status, tank conditions, and system alerts remotely, providing an added safeguard for community operators when hardware or water-storage issues occur.

Web-based monitoring and control interface

In addition to the physical control panel, the PSRO prototype is equipped with a web-based monitoring interface designed to support remote observation of key operating parameters (Nagarajan *et al.* 2025). This digital layer enables users or community operators to monitor the RO process without direct access to the hydraulic components, improving safety, accessibility, and response time in the event of performance degradation.

Figure 4(a) shows the system's main dashboard, displaying unit status, number of registered devices, and a simplified process schematic for quick identification of abnormal operating conditions. This overview page is intended for nontechnical operators, allowing them to verify whether a unit is functioning normally at a glance.

Figure 4(b) presents the real-time parameter display used during testing. The interface visualizes feed flow rate, feed and permeate pressure, permeate volume, and TDS output through gauge-style indicators. These visualization tools allow operators to identify fouling-related pressure drops, salinity spikes, or unstable recovery ratios without requiring technical interpretation of raw sensor values.

Together, the web dashboard and real-time monitoring interface provide a remote-access layer that complements the PSRO hardware. Although the implementation remains prototype level, the digital interface demonstrates the feasibility of community-operated RO units supported by simplified remote diagnostics.

Mobile application for remote control and alerts

To complement the web-based dashboard, the PSRO system includes a mobile application designed to provide users with real-time access to operational information and device status. While the web interface supports detailed monitoring, the mobile application focuses on rapid, user-friendly interaction, particularly important for community operators who rely on mobile devices rather than desktop terminals.

Figure 5(a) shows the mobile home screen, which provides immediate visibility of the unit's operational state (ON/OFF), basic feed and permeate conditions, and current water production. This lightweight interface allows users to confirm system status at any time, without requiring onsite presence.

Figure 5(b) illustrates the parameter monitoring view, where users can observe key indicators such as feed pressure, permeate pressure, flow rate, and TDS output. The layout emphasizes large, high-contrast components to support quick interpretation during field use, even under limited lighting or network conditions.

In addition to monitoring, the mobile application integrates a notification module that alerts users to abnormalities such as excessive feed pressure, abnormal TDS rise, empty raw water tank, or system shutdown events. Although the current version does not implement full remote actuation, the alert system provides early warnings that help prevent membrane fouling, dry running of pumps, and unexpected downtime.

Together with the physical control panel and web-based dashboard, the mobile application establishes a three-layer human-machine interface that supports decentralized RO operation. This multiplatform approach ensures that PSRO units can be monitored and maintained by nontechnical users across varied contexts, aligning with the system's intended deployment in remote coastal communities.

Performance testing of the PSRO prototype

Performance testing was conducted to evaluate the hydraulic stability, water-quality improvement, and operational feasibility of the PSRO configuration under brackish water conditions representative of Indonesian coastal areas. Tests were carried out using several types of raw water, including brackish groundwater, well water with variable salinity intrusion, and pre-treated household wastewater (greywater). Each test cycle was run for 60–90 min after a 10–15 min stabilization period.

Feedwater profile

The feedwater characterization revealed moderate salinity levels consistent with brackish conditions. Key parameters measured included TDS, EC, pH, temperature, and turbidity.

All values presented in Table 1 were obtained from experimental measurements conducted during system operation.

Permeate quality and salt rejection

The PSRO system demonstrated consistent TDS reduction across all test scenarios. Permeate TDS values were significantly lower than feedwater, meeting common thresholds for nonpotable household use and water-preparation requirements.

Salt rejection was calculated using (El-Kanj *et al.* 2025):

$$\text{Rejection}(\%) = \frac{\text{TDS}_{\text{feed}} - \text{TDS}_{\text{permeate}}}{\text{TDS}_{\text{feed}}} \times 100 \quad (3)$$

The performance index was calculated using Equation (3).

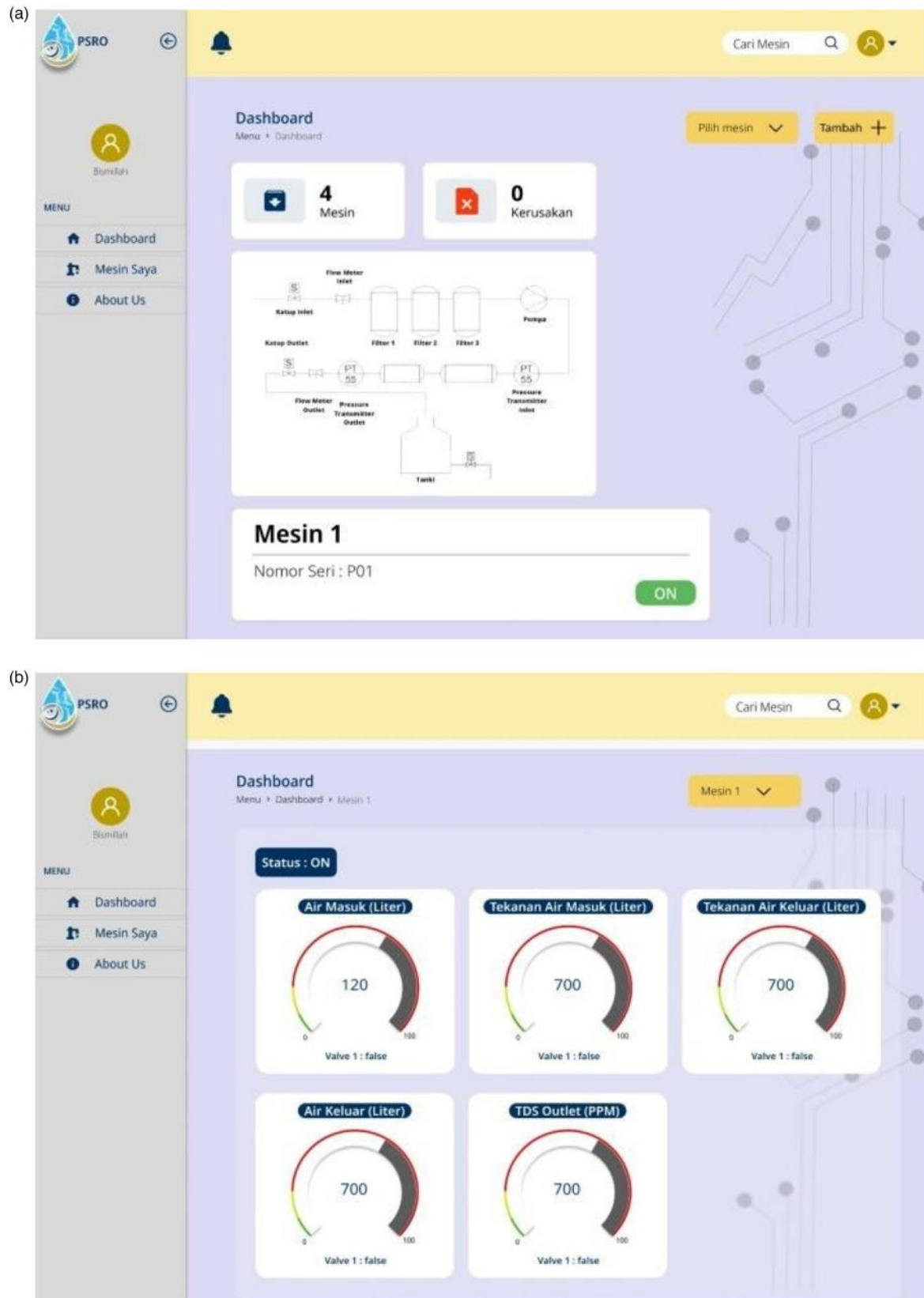


Figure 4 | (a) Web-based dashboard of the PSRO system providing unit status, system overview, and quick operational diagnostics. (b) Real-time monitoring interface displaying feed pressure, permeate pressure, flow rate, and TDS output for remote operational assessment.

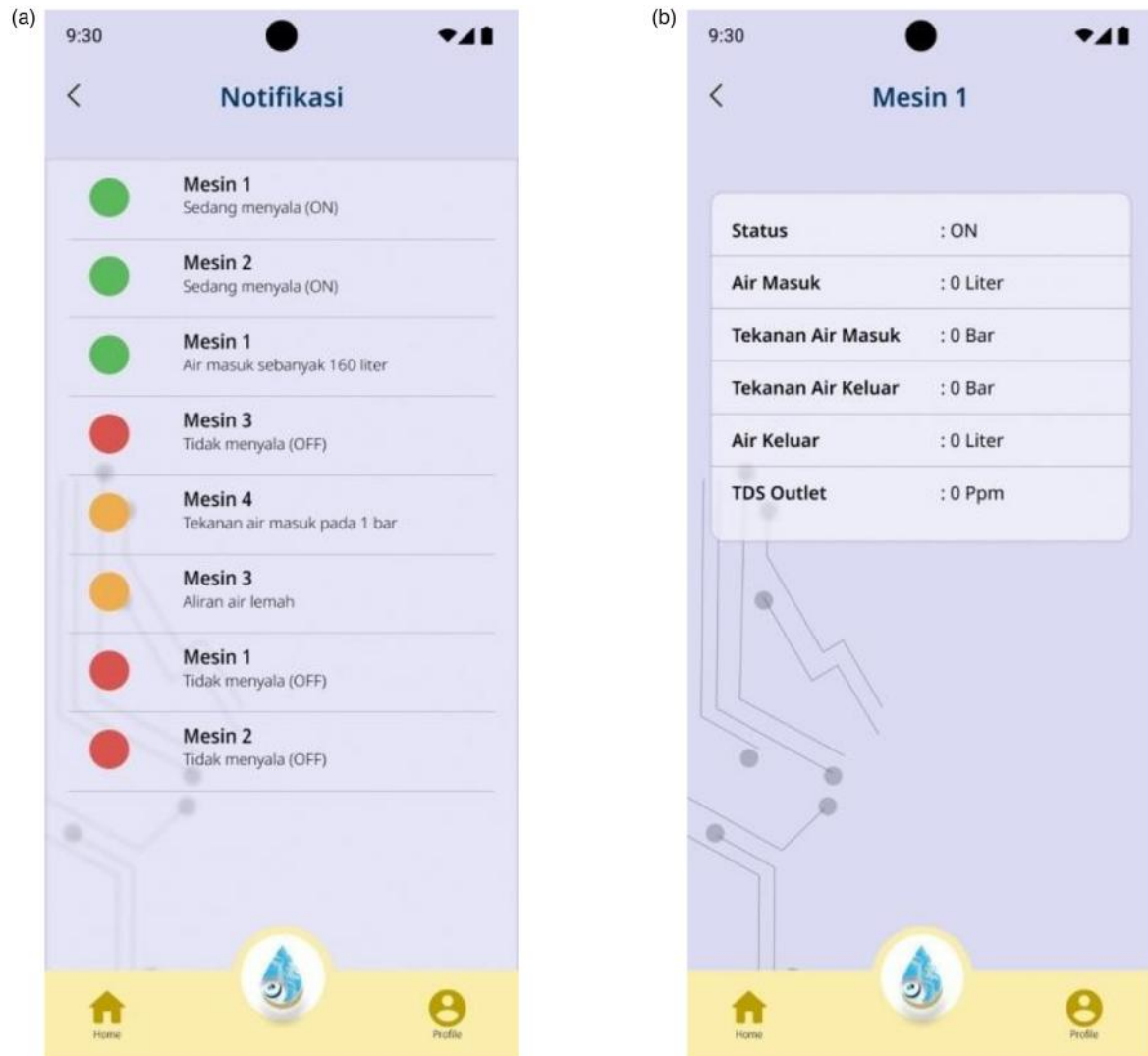


Figure 5 | (a) Mobile application home screen showing basic PSRO unit status and key operational indicators. (b) Mobile application monitoring interface with real-time feed pressure, permeate pressure, flow rate, and TDS measurements.

Table 1 | Summarizes the raw-water characteristics used during the test cycles

Water type	TDS (ppm)	pH	Salinity (ppt)	Turbidity (NTU)	Temp (°C)	Technical purpose
Brackish groundwater (target water)	1,500–2,500	7.3–7.6	1.2–2.0	2–4	28–30	Represents typical coastal brackish water; used for calibration and pressure-regulation testing.
Shallow groundwater (urban well)	215	7.1–7.3	<0.1	1–2	28	Used to validate performance under low-TDS feed and to verify inlet/outlet sensor accuracy.
Coffee-contaminated greywater	≥1,000	6.0–6.3	0	10–13	29	Simulates organic rich household greywater; stresses membrane fouling and TDS sensor sensitivity.
Detergent-contaminated greywater	314	7.7–8.0	0	8–10	29	Represents surfactant laden water to test fouling tendency and permeate stability.
PDAM tap water (treated municipal water)	70–120	7.0–7.4	<0.1	1–3	28–29	Used to evaluate PSRO under clean, low-salinity feed; serves as baseline for polishing-type operation.

Table 2 includes both experimentally measured values and design-based reference values. Experimental results are reported for permeate quality, while feedwater ranges represent target design conditions used for system evaluation.

Table 2 | Presents the feed–permeate comparison results, including rejection efficiency and steady-state permeate flow rate

Water Type	Feed TDS (ppm)	Permeate TDS (ppm)	Salt Rejection (%)	Notes
Brackish groundwater (target water)	1,500–2,500	80–120	92–95%	Estimated based on standard BWRO performance; included to represent design target water.
Shallow groundwater (urban well)	215	24	88.84%	Actual test result from prototype; low-TDS feed for sensor accuracy validation.
Coffee-contaminated greywater	≥1,000	23	97.70%	High-TDS organic greywater used to verify membrane consistency and TDS sensor sensitivity.
Detergent-contaminated greywater	314	23	92.68%	Surfactant-rich greywater representative of household wastewater.
Tap water (PDAM)	120–180	18–22	85–90%	Low-TDS municipal water to validate baseline performance.

Across all water samples, the prototype maintained rejection efficiencies in the expected range for brackish water RO membranes, confirming the suitability of the membrane selection and pretreatment scheme.

Recovery ratio and flow stability

Operational recovery rate was measured as the proportion of feedwater converted to permeate:

$$\text{Recovery}(\%) = \frac{\text{Volume of permeate}}{\text{Volume of feed}} \times 100 \quad (4)$$

The operational recovery rate was calculated using Equation (4).

Recovery values remained stable across test cycles, with only minor variations associated with feed salinity and temperature. Flow-rate readings remained within the acceptable operating window, confirming pump adequacy and stable hydraulic behavior.

The values presented in Table 3 are based on experimental measurements obtained during system operation, with recovery ratios calculated using Equation (4).

Table 3 | Shows recovery ratios and flow-rate behavior during the tests

Water type	Feed volume (L)	Permeate volume (L)	Recovery ratio (%)	Flow stability notes
Brackish groundwater (target water)	2,000	1,800	90%	Stable pressure at 8–12 bar; permeate flow decline <5% during 20-min cycle.
Shallow groundwater (urban well)	2,500	2,200	88%	Highly stable due to low salinity; minimal fouling tendency.
Tap water (PDAM)	3,000	2,800	93%	Best stability; constant inlet pressure and near-steady permeate rate.
Coffee-contaminated greywater	—	—	—	Not evaluated for recovery; used only for TDS/membrane-response validation due to organic load.
Detergent-contaminated greywater	—	—	—	Not evaluated for recovery; surfactant content unsuitable for recovery performance assessment.

The relatively high recovery ratios observed in this study are attributed to the controlled operating conditions of the PSRO system, including moderate feed salinity, stable operating pressure, and short operating cycles. The recovery values obtained (approximately 85–90%) remain within the upper range reported for small-scale

BWRO systems operating under low-fouling and optimized hydraulic conditions. Similar recovery ranges have been reported in previous studies on brackish water RO systems operated under controlled laboratory or pilot-scale conditions.

Pressure behavior and membrane stability

Pressure monitoring showed that the high-pressure pump maintained stable operating pressure within the 8–15 bar range, depending on feedwater salinity. Brackish groundwater required the highest pressure load (10–12 bar), while shallow-well and PDAM water operated at lower and more stable levels (8–10 bar) with fluctuations under 0.2 bar. These results indicate that the pretreatment stage effectively reduced particulate loading, and the concentrate control valve successfully dampened pressure spikes, one of the hybrid operational features adapted from small SWRO systems.

Throughout all test cycles, no abrupt pressure dips or oscillations were observed during start-up, steady-state operation, or flushing. The consistent hydraulic profile aligns with the stable permeate TDS values (18–24 ppm for all nonbrackish samples), suggesting that the membrane experienced uniform loading without early fouling.

Although coffee- and detergent-based greywater are not intended for long-term RO operation, the membrane remained stable during short-cycle exposure, indicating that the PSRO's simplified hydraulic design provides adequate protection without the need for advanced pressure-regulation hardware.

Operational observations

Operational observations during testing showed that the PSRO prototype behaved consistently and was simple to operate, even for nontechnical users. Start-up flushing reached steady state conditions within 1–2 min, and switching between water types required no additional calibration. Sensor readings including feed/permeate TDS, pressure, flow, and water level were stable and responsive throughout all cycles.

Additional observations include:

- No significant fouling occurred during short-cycle tests.
- Pretreatment (sediment + carbon) effectively reduced turbidity and prevented membrane clogging.
- Flowmeter readings allowed early identification of minor imbalances between feed and concentrate lines.
- Low-cost TDS sensors responded quickly but showed limited sensitivity for predictive fouling detection, an expected limitation for decentralized systems.

These findings reinforce the suitability of the PSRO configuration for decentralized household or community operation, where routine tasks such as flushing, cartridge replacement, and basic troubleshooting can be performed without specialized technical assistance.

DISCUSSION

The performance evaluation demonstrates that the PSRO system can provide stable brackish water purification with simplified operation suitable for decentralized deployment in coastal communities. The consistently low permeate TDS (18–24 ppm) across nonbrackish test waters indicates that the membrane operated within optimal rejection ranges despite the reduced complexity of the hydraulic layout. This aligns with reported rejection performance of compact BWRO systems, confirming that simplified configurations can still achieve high-quality permeate when adequately supported by pretreatment.

The pressure behavior observed during testing further supports this interpretation. Stable operating pressure within the 8–15 bar range and minimal fluctuation across all cycles suggest that the hybrid BWRO–SWRO operational scheme effectively stabilizes hydraulic loading. This finding is notable because small RO systems frequently experience pressure instability due to pump overshoot, rapid fouling, or insufficient concentrate control. The PSRO's stable hydraulic profile, therefore, indicates increased robustness compared with typical low-cost domestic RO configurations.

Recovery ratios between 88 and 93% across applicable water types indicate efficient water utilization and minimal feedwater waste, which is essential for small island or coastal settings where freshwater availability is severely limited. While the absolute values may vary in real coastal brackish groundwater, the prototype results demonstrate that the system can operate in high recovery mode without compromising pressure stability or permeate quality. This operational balance is typically achieved through more complex RO installations, suggesting that PSRO introduces a practical pathway toward sustainable small-scale desalination.

From an operational perspective, the system's simplicity is an important outcome. All routine tasks, flushing, monitoring, and adjusting concentrate flow were manageable for nontechnical users. This addresses a key gap identified in the literature, as many existing RO installations in coastal Indonesia remain dependent on centralized facilities and trained technicians. By enabling independent operation and simplified maintenance, PSRO has the potential to reduce downtime and improve water accessibility in distributed coastal regions.

The greywater and low-TDS tests, although not representative of target feedwater, provide additional insight into the sensitivity and limitations of the low-cost sensor set. The ESP32-based module was effective for real-time TDS and pressure monitoring but lacked the sensitivity required for predictive fouling detection, consistent with observations from similar low-cost IoT-based RO monitoring systems. These limitations highlight future opportunities for improving the sensing layer through more advanced predictive algorithms or enhanced sensor calibration, while keeping the hardware simple.

Overall, the results confirm that the PSRO framework is technically feasible, operationally stable, and adaptable for decentralized water treatment in coastal environments, offering a practical alternative to centralized SWRO/BWRO systems that currently dominate Indonesian coastal water infrastructure.

CONCLUSION

This work introduced the PSRO concept as a practical framework for decentralized brackish water treatment in coastal settings. The prototype demonstrated that a simplified BWRO-based configuration supported by basic pre-treatment and minimal sensing can operate reliably without complex supervision. The results confirm that decentralized RO is technically achievable with reduced component requirements, opening opportunities for community-level water provision in areas where centralized SWRO/BWRO facilities are difficult to maintain.

More broadly, this study shows that membrane desalination for small coastal communities does not necessarily require high-cost instrumentation or specialized personnel. By emphasizing operational simplicity and stable performance rather than hardware sophistication, the PSRO approach provides a feasible and adaptable pathway for expanding freshwater access in resource-limited environments.

While the PSRO prototype operated reliably under the experimental conditions, the present study was limited to short-cycle testing and did not evaluate long-term fouling behavior, biofilm growth, or membrane ageing. These factors are expected to influence performance stability in real community deployment. In addition, the sensing layer based on low-cost instruments provided functional monitoring but lacked the precision required for diagnosing early membrane deterioration.

Future research should extend the evaluation period, integrate more advanced sensing or predictive diagnostics, and validate performance under broader feedwater variations across multiple coastal regions. Further scaling analysis, including multi membrane configurations and flow-capacity optimization, is also required to determine the suitability of the PSRO framework for small community clusters rather than single-household operation.

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AUTHOR CONTRIBUTIONS

The author is solely responsible for the conceptualization, system design, data acquisition, prototype development, analysis, interpretation, and manuscript preparation.

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DATA AVAILABILITY STATEMENT

Data cannot be made publicly available; readers should contact the corresponding author for details.

CONFLICT OF INTEREST

The authors declare there is no conflict.

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