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Improving Peat Water Quality Using a Multi-stage Shell Sand, CTO, and Reverse Osmosis System in Sengkubang Village, Indonesia

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Abstract
In many Indonesian peatland regions, communities still rely on peat water for drinking despite its very low pH, dark colour, and elevated loads of natural organic matter and dissolved metals. This study evaluates the performance of a small-scale, multi-stage treatment system that combines shell sand, CTO carbon block filtration, and reverse osmosis (RO) to improve peat water quality in Sengkubang Village with reference to Indonesian Regulation Permenkes No. 32/2017. A quasi experimental one group pretest–posttest design was applied, measuring total dissolved solids (TDS), turbidity, colour, odour, pH, iron (Fe) and manganese (Mn) in raw and treated water. The system substantially reduced turbidity and colour, with both parameters decreasing by more than 90 percent, and lowered TDS while keeping it well below the national limit. The pH shifted from strongly acidic to near neutral, and Fe was reduced to a small fraction of its initial concentration, far below both national and WHO oriented guideline values, whereas Mn remained safely below its standard. After treatment, all monitored parameters complied with Permenkes 32/2017. The results indicate that locally sourced shell sand can function as an effective pretreatment for RO in humic rich, acidic peat water when combined with CTO adsorption. Nevertheless, the findings are based on a single site and short observation period and do not include microbiological indicators, so the system should be regarded as a promising but still preliminary option that requires further seasonal, long term, and microbiological assessment.

Keywords: peat water; shell sand; CTO carbon filter; reverse osmosis; drinking water quality

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INTRODUCTION

Access to safe drinking water remains a persistent challenge in many regions of Indonesia, particularly where communities depend on surface and groundwater sources with limited treatment. In peatland-dominated areas, such as large parts of Sumatra and Kalimantan, the use of peat water as a raw water source introduces specific health and technical risks that are not trivial. Peat water is typically characterized by low pH, high color, and elevated concentrations of dissolved organic matter and metals, conditions that complicate conventional treatment and may compromise public health if not addressed appropriately.

A central concern in peat-derived water is the high content of natural organic matter, particularly humic and fulvic acids. These macromolecules, released from the decomposition of organic material in peat soils, strongly affect water color, taste, and odor, and interfere with disinfection processes. At high concentrations, humic and fulvic substances can form disinfection by-products (DBPs) during chlorination, and several DBPs are associated with carcinogenic and other long-term health risks (Ji et al., 2020). They can also hinder microbial inactivation and promote the regrowth of microorganisms in distribution systems (Wu et al., 2021). From a user perspective, dark color and unpleasant taste or smell reduce acceptability, which may drive households to alternative, sometimes poorly regulated sources such as refill depots.

Beyond natural organic matter, heavy metal contamination in drinking water derived from various sources, including peat and shallow groundwater, has been repeatedly reported in Indonesia. Arsenic, cadmium, and lead are of particular concern because of their cumulative toxic effects, especially in children. Studies on refill drinking water have found that a notable proportion of samples did not comply with national regulations, either due to excessive heavy metal concentrations or microbiological contamination (Rahmawati & Lumbantobing, 2023; Royani & Fitriana, 2020). Lead exposure through drinking water has been linked to developmental problems and malnutrition among toddlers in Indonesian settings, indicating that even low-level, chronic exposure can have measurable health consequences (Fadillah et al., 2022). These findings suggest that reliance on unmonitored or poorly monitored small-scale water suppliers cannot be viewed as a fully safe alternative to self-treatment of local raw water.

Microbiological contamination adds another layer of risk. The presence of Escherichia coli and other coliform bacteria in drinking water is closely associated with diarrheal disease, undernutrition, and increased child morbidity. Poor sanitation, unsafe storage, and inadequate treatment at the point of collection or point of use are well-documented drivers of contamination in Indonesia, particularly in dense urban and peri-urban settlements (Yamauchi et al., 2022; Otsuka et al., 2019; Patunru, 2015). Studies have reported that many communal sources and refill depots show coliform levels exceeding both national and international safety limits (Rosmiaty et al., 2019; Wahyuni et al., 2019). This pattern indicates that formal adherence to standards on paper does not automatically translate into safe water at the household level.

Attention has also been drawn to metals such as iron and manganese, which are often elevated in groundwater and peat-related sources. While these metals are frequently treated as “aesthetic” problems because they cause color, staining, and metallic taste, sustained exposure at high concentrations can contribute to gastrointestinal complaints and may interact with other nutritional and environmental stressors (Lowe et al., 2021). Given that peat water often has both low pH and elevated Fe and Mn, any feasible treatment system for rural communities needs to address these parameters alongside organic matter and microbial safety.

The regulatory framework for drinking water in Indonesia is primarily defined by the Regulation of the Minister of Health No. 32 of 2017 (Permenkes 32/2017). This regulation specifies physical, chemical, and microbiological limits for parameters such as turbidity, color, TDS, pH, Fe, Mn, sulfate, and coliform bacteria. For example, several reports refer to maximum permissible levels of 1 mg/L for iron and 0.5 mg/L for manganese, along with sulfate at 250 mg/L (Zulya et al., 2022; Sari et al., 2023). Other work that discusses later revisions presents 0.3 mg/L for iron and 0.5 mg/L for manganese, with chloride limited to 250 mg/L, and emphasizes turbidity and color limits in the range of 5 NTU and 15 TCU respectively (Khoeriyah & Anies, 2015;). Microbiological standards require zero coliform bacteria per 100 mL, consistent with the preventive approach to waterborne disease (Khoeriyah & Anies, 2015). These differences in reported numeric values partly reflect changes over time, but they also show that enforcement and interpretation are not always consistent across studies and local authorities.

When compared to the World Health Organization (WHO) guideline values, Indonesian standards appear to be moving toward closer alignment but have historically allowed higher limits for some parameters. WHO recommends a guideline value of 0.3 mg/L for iron in drinking water, which is often treated as an aesthetic threshold rather than a strict health-based limit (Amano et al., 2020; Novikov et al., 2021). Earlier Indonesian regulations cited higher permissible concentrations, although more recent interpretations suggest convergence with WHO recommendations (Amano et al., 2020). For microbiological safety, both WHO and Indonesian regulations agree on the requirement of zero total coliforms in drinking water (Novikov et al., 2021). Heavy metal contamination related to mining and other industrial activities has been documented in various regions, raising questions about the capacity of current monitoring and enforcement systems to ensure that standards are effectively implemented at community level (Basri et al., 2022).

In this context, technical solutions that can reliably improve peat water quality to meet or approach these standards are needed, especially where centralized treatment and piped supply are absent. One group of options involves adsorption and filtration using locally available media. Activated carbon, particularly in the form of carbon block CTO (Chlorine, Taste, Odor) filters, has been widely used to remove natural organic matter, color, and odor through adsorption processes (Schmit & Wells, 2002; Yin et al., 2023). In peat water, activated carbon has shown effectiveness in reducing dissolved organic compounds and color intensity, leading to clearer and more acceptable water (Khair, 2016; Purwanti et al., 2021). Filtration systems that combine sand and activated carbon can further reduce turbidity and organic load, and have been reported to help peat water meet relevant drinking water criteria (Hamzani et al., 2014; Setyobudiarso & Yuwono, 2014; Wilian et al., 2019; Ismillayli et al., 2018; Saputri et al., 2025).

Another promising avenue is the use of calcium carbonate rich materials such as shell sand or crushed seashells. These materials can neutralize acidity and promote the removal or precipitation of iron and manganese. In Indonesian coastal and riverine communities, shell waste is abundant, relatively inexpensive, and culturally familiar, making it an attractive candidate for local water treatment media. Although several studies have examined shell-based media for improving groundwater or surface water quality, systematic evaluations for strongly acidic, high-color peat water are still limited.

Reverse osmosis (RO) has also been introduced in peat water treatment schemes. RO membranes are capable of removing dissolved salts, organic molecules, and microorganisms, and several studies in Indonesia report high removal efficiencies for TDS, color, and organic matter in peat-related waters when RO is used after conventional pretreatment steps (Setiadi & Kristyawan, 2018; Agnestisia et al., 2022; Mardhatillah et al., 2023). At the same time, RO performance is sensitive to fouling, especially when treating humic-rich water, which means that appropriate pretreatment to remove turbidity and a substantial fraction of dissolved organics is essential to maintain membrane lifespan and operating costs (Khair, 2016).

Most existing work on peat water treatment in Indonesia has focused either on single media systems, such as sand or activated carbon filters, or on combinations of coagulation–filtration–RO at pilot or facility scale (Khair, 2016; Setiadi & Kristyawan, 2018; Purwanti et al., 2021; Agnestisia et al., 2022; Mardhatillah et al., 2023; Saputri et al., 2025). There is much less empirical evidence on integrated, small-scale systems that combine locally sourced shell sand, CTO carbon block filtration, and RO in a single treatment train for highly acidic peat water, particularly in rural communities that rely directly on nearby peatland sources. This gap is relevant for villages such as Sengkubang in Mempawah Regency, West Kalimantan, where households still depend heavily on rainwater and untreated peat or shallow groundwater and where centralized services are not yet available.

The present study addresses this gap by evaluating the effectiveness of a multi-stage filtration system that combines shell sand, CTO carbon filtration, and reverse osmosis for treating peat water in Desa Sengkubang. The focus is on assessing whether this combination can reduce key physical and chemical parameters, including TDS, turbidity, color, pH, iron, and manganese, to comply with or approach the requirements of Permenkes 32/2017. At the same time, the study seeks to explore the potential of locally accessible materials and relatively simple technology configurations as a realistic option for improving drinking water quality in rural peatland contexts.

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METHODS

This study employed a quasi-experimental design using a one-group pretest–posttest model to evaluate the effectiveness of a three-stage filtration system (shell-sand, CTO carbon block, and reverse osmosis) in improving the quality of peat water in Sengkubang Village. This design allows for direct measurement of changes in water quality before and after treatment without the need for a control group.

Research Procedures

The research procedures followed the sequence illustrated in Figure 1, beginning with a field survey to assess the condition of the peat water source, community needs, and the planned installation site. The next step involved preparing tools and materials, including inspection and sterilization of filtration components and pumps. The filtration unit was then installed according to the technical design, followed by an operational demonstration to ensure all media functioned properly. After system verification, peat water samples were collected, filtered, and subsequently subjected to laboratory analysis.

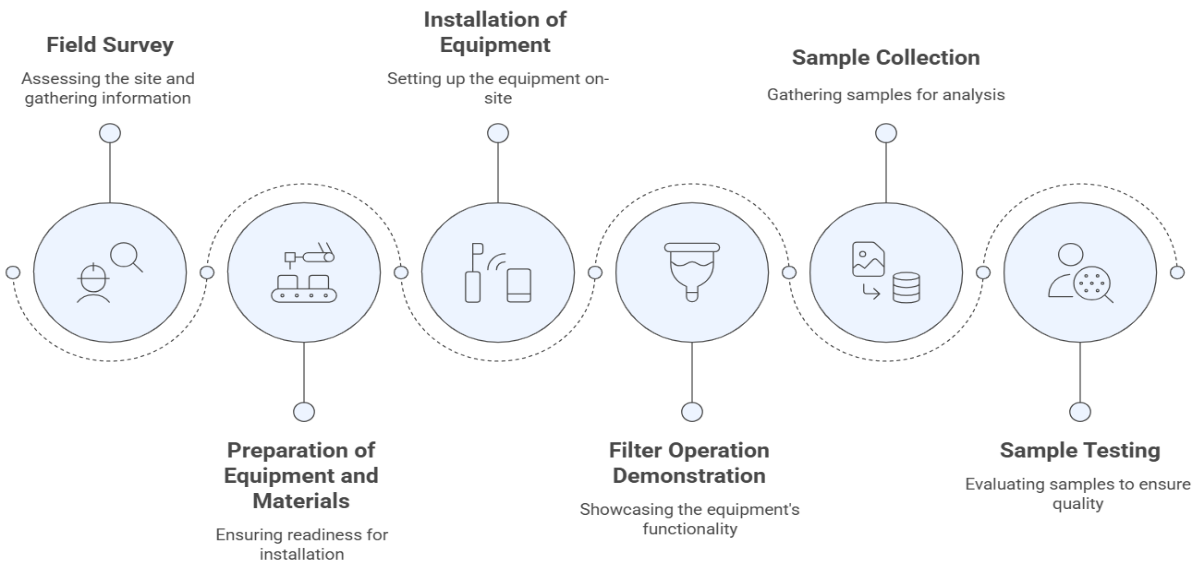

Figure 1. Equipment Installation and Testing Process

Filtration System Design

The complete system design is shown in **Figure 2**, consisting of 300–500 L water tanks, structural stands, a distribution pump, an FRP 1054 tank filled with shell sand, CTO and GAC carbon filters, a sediment filter, and a reverse osmosis (RO) unit equipped with a membrane and UV lamp. The filtration process includes three stages:

1. Shell-sand filtration to increase pH, reduce color, and facilitate metal precipitation;
2. Carbon filtration (CTO–GAC) to adsorb organic matter, odors, and fine particles; and
3. Reverse osmosis for the removal of dissolved solids, metal ions, and micro-contaminants.The system operates at a flow rate of approximately 1 L/min with RO pressure ranging from 80–100 psi.

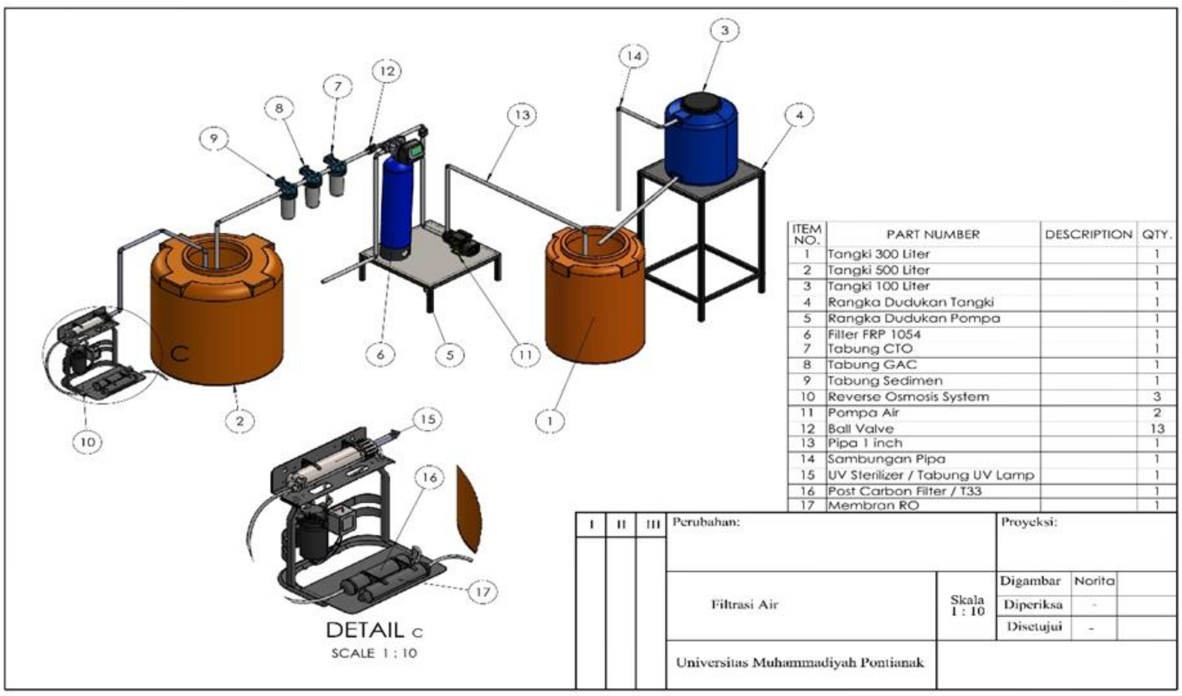

Figure 2. Filtration Design and Components

Sample Collection and Water Quality Parameters

Peat water samples were collected using a grab sampling technique from the same point source to maintain sample consistency. Each sample was tested in two stages: pretest (before filtration) and posttest (after passing through all filtration stages). The analyzed parameters included TDS, turbidity, color, odor, pH, Fe, and Mn, referring to the Indonesian National Drinking Water Standards (Permenkes No. 32/2017). Laboratory analyses were performed using a digital TDS meter, turbidimeter, pH meter, spectrophotometer, and Atomic Absorption Spectrophotometry (AAS) for Fe and Mn.

Filtration Procedure and Data Analysis

Each sample was filtered continuously through the system and collected in a sterile container for laboratory testing. Data analysis was conducted descriptively using a comparative approach by evaluating pretest and posttest values and calculating the percentage reduction for each parameter. Interpretation of effectiveness was based on known physicochemical mechanisms such as carbon adsorption, metal precipitation, and molecular removal through RO membranes.

Ethical Considerations

This study received ethical approval from the Ethics Committee of the Faculty of Health Sciences, Muhammadiyah University of Pontianak (No. 014/KEPK-FikPsi/UMPONTIANAK/2025).

RESULTS AND DISCUSSION

The performance of the shell sand–CTO–RO system was evaluated using physical and chemical parameters of peat water sampled in Desa Sengkubang. The numerical results are summarised in Table 1 and Table 2, while Table 3 presents the percentage reductions and compliance status relative to Permenkes No. 32/2017. To support the numerical data, Figure 2 shows the visual change in water colour before and after treatment, and Figure 3 and Figure 4 illustrate the parameter changes graphically.

Physical parameters

The physical characteristics of the peat water before and after treatment are shown in Table 1. The raw peat water had a TDS of 101 mg/L, turbidity of 22.6 NTU, and colour of 631.2679 PtCo. After treatment, TDS decreased to 24 mg/L, turbidity to less than 1.19 NTU, and colour to 34.6471 PtCo. Odour was reported as "not smelly" both before and after treatment.

Table 1. Laboratory results for physical parameters of peat water in Desa Sengkubang before and after treatment and the maximum limits of Permenkes No. 32/2017.

Physical parameter	Unit	Before treatment	After treatment	Permenkes 32/2017 limit
TDS	mg/L	101	24	< 300
Turbidity	NTU	22.6	< 1.19	< 3
Colour	PtCo	631.2679	34.6471	50
Odour	–	Not smelly	Not smelly	Not smelly

The reduction in turbidity and colour is also visible in Figure 2, which contrasts photographs of raw peat water and treated water in transparent containers. The raw sample appears dark brown and opaque, whereas the treated sample is much lighter and visually clearer, consistent with the colour and turbidity values in Table 1.

Chemical parameters

The chemical quality of the peat water is summarised in Table 2. Initially, the water was strongly acidic with a pH of 3.66, and contained Fe and Mn at 0.8714 mg/L and 0.035 mg/L respectively. After treatment, pH increased to 6.91, Fe dropped to 0.0406 mg/L, and Mn slightly decreased to 0.033 mg/L.

Table 2. Laboratory results for chemical parameters of peat water in Desa Sengkubang before and after treatment and the maximum limits of Permenkes No. 32/2017.

Chemical parameter	Unit	Before treatment	After treatment	Permenkes 32/2017 limit
pH	–	3.66	6.91	6.5–8.5
Iron (Fe)	mg/L	0.8714	0.0406	1
Manganese (Mn)	mg/L	0.035	0.033	0.5

The changes in pH, Fe, and Mn are illustrated in Figure 4 as paired bars. The figure shows the substantial shift of pH from strongly acidic to near neutral, a large reduction in Fe, and a modest change in Mn, with all parameters complying with the Permenkes limits after treatment.

To summarise both sets of results, Table 3 quantifies the percentage reductions for each parameter (taking 1.19 NTU as the conservative upper bound for turbidity) and states whether the water met the standard before and after treatment.

Table 3. Percentage reduction of key parameters and compliance with Permenkes No. 32/2017.

Parameter	Unit	Before	After	Approx. reduction (%)	Compliance status
TDS	mg/L	101	24	76.2	Compliant before and after
Turbidity	NTU	22.6	<1.19	≥94.7	Non-compliant before; compliant after
Colour	PtCo	631.27	34.65	94.5	Non-compliant before; compliant after
pH	–	3.66	6.91	– (pH shift)	Non-compliant before; compliant after
Fe	mg/L	0.8714	0.0406	95.3	Compliant (national limit) before and after; further improved
Mn	mg/L	0.035	0.033	5.7	Compliant before and after

As Table 3 shows, the system led to large reductions in turbidity, colour, and Fe and successfully shifted pH into the permitted range. Mn was already low and changed only slightly.

Interpretation of physical parameter changes

The substantial improvement in turbidity and colour (Tables 1 and 3; Figures 2 and 3) indicates that the filtration train effectively targeted the suspended solids and dissolved organic matter that ominate peat water appearance. The turbidity reduction of at least 94.7 % suggests efficient retention of fine particles by the shell sand and CTO stages, with further polishing by the RO membrane. This aligns with previous evidence that sand- or shell-based filters can remove particulates effectively when operated at appropriate loading rates, and that carbon block filters contribute both mechanical filtration and adsorption (Nurfida & Widiasa, 2018; Farsad et al., 2023).

The >94 % reduction in colour, with final values well below the 50 PtCo limit, confirms that the system removed a large fraction of humic and fulvic substances, which are largely responsible for the dark colour of peat water (Dong et al., 2019; Khair, 2016; Purwanti et al., 2021). The visual contrast between the raw and treated water in Figure 2 strengthens this conclusion. Activated carbon is known to adsorb a wide range of natural organic matter (Schmit & Wells, 2002; Yin et al., 2023), and its role in this study is consistent with findings from multistage peat water treatment systems that combine sand and activated carbon (Hamzani et al., 2014; Setyobudiarso & Yuwono, 2014; Wilian et al., 2019; Ismillayli et al., 2018; Saputri et al., 2025). The remaining colour (around 35 PtCo) indicates that some dissolved organics are still present, but from a regulatory standpoint the water is acceptable.

TDS reductions of about 76 % (Table 3) demonstrate that the RO unit was functioning as expected, even though both the initial and final TDS values are below the threshold of 300 mg/L. This confirms that the system provides “extra” polishing of dissolved ions and low-molecular-weight organics. Since high TDS was not the primary problem in this case, the added value here is more about taste and prevention of scaling than about compliance with the standard.

Odour showed no change, which is consistent with the baseline description of the raw water as “not smelly”. Although CTO filters and activated carbon generally help remove taste and odour compounds (Wu et al., 2021), this effect cannot be assessed clearly in this study because the initial odour was already acceptable.

Interpretation of chemical parameter changes

The shift in pH from 3.66 to 6.91 (Table 2) is important both chemically and from a health and infrastructure perspective. At pH 3.66, water is corrosive and uncomfortable to drink. It also keeps Fe and Mn in more soluble forms (Aydın et al., 2021; Arifianingsih et al., 2020). The near neutral pH after treatment indicates that the shell sand (oyster shell) media dissolved sufficiently to neutralise the acidity. This is consistent with the behaviour of $CaCO_3$-based materials, which raise pH and facilitate metal precipitation.

The Fe concentration dropped by more than 95 %, from 0.8714 to 0.0406 mg/L (Table 3). Even though the initial Fe was still under the national limit of 1 mg/L, the treated water falls well below both national and WHO-oriented thresholds (Amano et al., 2020; Novikov et al., 2021). Literature on oyster shell filters supports this pattern: their high surface area and porosity provide sites for adsorption and co-precipitation of Fe, especially when aeration allows Fe(II) to oxidise to Fe(III) and form insoluble hydroxides (Safitri & Purnomo, 2023; Aziz et al., 2020). The present results are in line with slow sand or biofilter systems that incorporate shell media and report strong Fe removal. Figure 4 visualises this reduction and shows that Fe is far below the limit after treatment.

Mn levels were low from the start (0.035 mg/L) and only decreased slightly to 0.033 mg/L. This small change is not enough to draw firm conclusions about Mn removal capacity. It is well known that Mn often requires higher pH or biological oxidation for effective removal (Aydın et al., 2021; Arifianingsih et al., 2020). The key point here is that the system maintained Mn safely below the 0.5 mg/L limit under the tested conditions. If the raw water had contained higher Mn, additional design measures (for example, enhanced aeration or longer contact time) might have been necessary.

Mechanisms and the role of each treatment stage

The patterns across Tables 1–3 and Figures 3–4 are consistent with a staged treatment mechanism:

1. Shell sand (oyster shell) stage. Increases pH and promotes Fe precipitation. Studies show that calcined or crushed oyster shells possess large surface areas that facilitate adsorption of Fe and Mn, and that their $CaCO_3$ matrix supports chemical and potentially biological removal pathways (Safitri & Purnomo, 2023; Shi et al., 2022; Aziz et al., 2020). The strong pH shift and Fe reduction in Table 2 support this interpretation.
2. CTO activated carbon stage. Adsorbs humic and fulvic acids and fine particulates, which explains the large reductions in colour and turbidity (Tables 1 and 3; Figure 3). The high surface area and porosity of activated carbon block filters are consistent with previous research on colour and organic matter removal (Nurfida & Widiasa, 2018; Dong et al., 2019; Hoslett et al., 2018; Plant et al., 2013; Farsad et al., 2023).
3. RO stage. Provides final removal of dissolved salts and remaining organics, reflected in the TDS reduction and further improvement in colour and turbidity. However, humic-rich water is known to cause RO fouling (Elma et al., 2021; Xia et al., 2013; Gao et al., 2023; Chen et al., 2015). The pretreatment by shell sand and CTO likely reduced the fouling potential. No flux decline data are presented here, so long-term performance remains uncertain.

The photograph of the system and filter arrangement (which can be presented as Figure 1 in the Methods) can help readers connect these mechanisms with the physical layout of the device. Including a flow diagram in the same figure will also make it easier to understand which parameters are primarily addressed in each stage.

Variability, limitations, and implications for practice

The results clearly show that, at the time of sampling, the system converted highly acidic, strongly coloured peat water into water that meets Permenkes No. 32/2017 for the measured parameters. However, the robustness of this performance needs a cautious interpretation.

Peat water quality varies seasonally with rainfall and hydrological changes (Wit et al., 2015; Rodrigues et al., 2018; Preite & Pearson, 2017; Buck et al., 2019). A conceptual diagram illustrating wet-season dilution and dry-season concentration effects could be included as an additional figure in the discussion (for example Figure 5: Seasonal drivers of peat water quality), to remind readers that the values in Tables 1–3 represent only one hydrological condition. Future work should repeat the measurements in different seasons to test how much "buffer capacity" the system has when the raw water becomes more extreme.

Long-term performance is another limitation. Empirical studies on household filters indicate that activated carbon media saturate and biofilm formation occurs after a few months, leading to reduced adsorption and potential bacterial regrowth (Sobsey et al., 2008; Murphy et al., 2010). RO membranes are also susceptible to fouling and require maintenance (Rosa et al., 2016; Clayton et al., 2024; Wu, 2024). None of these ageing processes were evaluated here. From a public health perspective, microbiological quality is crucial, yet this study did not measure coliforms or E. coli, even though these are major contributors to disease risk in Indonesia (Yamauchi et al., 2022; Otsuka et al., 2019; Patunru, 2015; Rosmiaty et al., 2019; Wahyuni et al., 2019). Including a table or figure in future work that tracks microbiological indicators alongside physical–chemical data over time would be important.

Finally, sustainability and user practice matter. Even an effective system can fail if cartridges are not replaced, RO units are not cleaned, or treated water is recontaminated during storage (Mellor et al., 2013; Mahaffy et al., 2014; Crider et al., 2023; Ren et al., 2013; Pham et al., 2017; Prüss-Üstün et al., 2019). This study focuses on technical feasibility, not on adoption or costs. A separate table summarising expected replacement intervals, approximate costs, and maintenance tasks per component could be added later if data are available, to connect the promising laboratory results with realistic implementation scenarios.

CONCLUSION

The study demonstrates that a multi-stage filtration system combining shell sand, CTO carbon block filtration, and reverse osmosis is technically capable of transforming highly acidic, strongly coloured peat water in Desa Sengkubang into water that meets the physical and chemical requirements of Permenkes No. 32/2017. The most critical problems of the raw peat water were low pH, high turbidity, and very high colour linked to humic and fulvic substances. After treatment, pH shifted from 3.66 to 6.91, turbidity fell from 22.6 NTU to below 1.19 NTU, and colour dropped from more than 630 PtCo to around 35 PtCo, while iron concentrations decreased by more than ninety per cent to well below the national and WHO-oriented guideline ranges. These changes indicate that shell sand effectively neutralised acidity and promoted iron removal, activated carbon in the CTO stage substantially reduced natural organic matter and associated colour, and reverse osmosis provided final polishing for dissolved solids and residual organics. For the set of parameters measured, the system shows that locally available $CaCO_3$-rich media can be integrated with commercially available filters and membranes to produce water of acceptable quality in a rural peatland setting.

At the same time, the evidence presented is still narrow in scope. The results represent a single location and a limited period of observation, without replication across seasons when peat water quality is known to vary. The initial manganese concentration was already low, so the data do not really test the system's capacity to treat Mn-rich sources. Moreover, the study focuses on physical and chemical parameters and does not address microbiological quality, even though microbial contamination is a major contributor to waterborne disease in Indonesia. Long-term behaviour of the shell sand media, CTO filter, and RO membrane was not evaluated, so issues such as adsorption exhaustion, fouling, and bacterial regrowth remain unanswered. In that sense, the findings should be read as a proof of concept for the technical feasibility of the shell sand–CTO–RO combination rather than as a full demonstration of a durable and comprehensive drinking water solution. The main contribution lies in showing that such a configuration can bring key peat-water parameters within regulatory limits using a mix of local and commercial components, while also clarifying where further work is needed before wide deployment can be responsibly recommended.

RECOMMENDATION

On the practical side, the results suggest that small-scale systems based on shell sand, CTO carbon blocks, and reverse osmosis could be piloted more broadly in peatland villages that lack access to piped water, provided that certain conditions are met. Local governments, universities, and community organisations that consider adopting similar systems should treat the design tested in Sengkubang as a starting point that still requires careful adaptation. Implementation should be accompanied by clear arrangements for operation and maintenance, including training residents to monitor simple indicators such as colour, turbidity, and pH, to replace shell sand and CTO cartridges at appropriate intervals, and to recognise signs of RO membrane fouling. Because the present study did not measure microbiological parameters, any practical use should be coupled with safe storage and, where feasible, residual disinfection to reduce the risk of recontamination between filtration and consumption. A cautious, stepwise roll-out using demonstration units, user education, and local cost-sharing mechanisms would be more defensible than immediate large-scale installation.

For research, several extensions are needed to strengthen the evidence base. Future studies should include repeated sampling across wet and dry seasons and, where possible, incorporate replicate measurements to characterise variability and uncertainty. Microbiological analyses, especially for total coliforms and E. coli, are essential if the system is to be proposed as a drinking water intervention, and should be observed over time to capture potential regrowth in filters and storage containers. Longer-term experiments are required to quantify the lifespan of shell sand media, CTO cartridges, and RO membranes under realistic use in rural households, including monitoring of flow rates, pressure, and changes in removal efficiency. Economic evaluation and comparison with alternative low-cost technologies, such as biosand or ceramic filters, would help clarify where the shell sand–CTO–RO configuration is most appropriate and where simpler options may suffice. It would also be useful to test the system at sites with higher initial concentrations of manganese and other metals, and to explore variations in media size, contact time, and aeration that might improve performance without raising costs. By addressing these aspects, future work can move from demonstrating technical potential at a single site toward developing a robust, context-sensitive option for improving drinking water quality in Indonesia's peatland communities.

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AUTHOR CONTRIBUTIONS

NRA was responsible for developing the article's conceptual framework and design, collecting and analyzing the data, interpreting the results, writing and revising the manuscript, and providing final approval for publication. SLV and LS collaborated in developing the article's conceptual framework, managing the data, conducting a critical review of the manuscript, and granting final approval for publication. NRA, SLV, and LS jointly contributed to the development of the data analysis and interpretation, and provided final approval for the publication version.

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