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Hydraulic Coagulation–Ultrafiltration for Peat Water in South Kalimantan

Sulaiman Hamzani[1], Syarifudin A., Fatmi Indah Hati, Tien Zubaidah*

Departement of Environmental Health, Poltekkes Kemenkes Banjarmasin, Indonesia

*Correspondence: tien.zubaidah@gmail.com

Access to safe drinking water remains a critical public health challenge in South Kalimantan, where peat-influenced water sources exhibit high turbidity, elevated iron concentrations, and acidic pH. This experimental study designed, fabricated, and evaluated a Circular Pipe–Synthetic Ultrafiltration (CP-SKU) device a hydraulic coagulation reactor requiring no mechanical energy input — for treatment of peat-influenced dug well water. Five sequential treatment configurations were tested in triplicate using PAC Powder (100 mg/L) as coagulant. The CP-SKU configuration achieved the best performance: turbidity reduction from 19.8 to 0.47 NTU (97.63%), iron below detection limit (<0.1 mg/L), and pH 6.72 — all compliant with Indonesian Ministry of Health Regulation No. 2 of 2023. Extended trials on high-turbidity raw water (83.67 NTU) confirmed 98% turbidity removal and 99.55% MPN Coliform reduction. However, effluent pH (6.39) fell marginally below the 6.5 regulatory threshold, and residual coliform indicators did not meet zero-tolerance standards, necessitating upstream pH correction and downstream disinfection prior to consumption.

Keywords: Circular pipe reactor, Hydraulic coagulation, Peat water, Turbidity removal, Ultrafiltration

INTRODUCTION

South Kalimantan is traversed by an extensive network of rivers, including the Barito (900 km), Martapura (600 km), Negara (85 km), and Tabalong (75 km), along with numerous tributaries (Widyanata et al., 2024). Water quality assessments of the Barito and Martapura rivers by the Regional Environmental Agency classified both as moderately to severely polluted (Tyastirin & Suprayogi, 2023). Riverine water quality in the region has deteriorated significantly due to riparian settlement expansion, erosion, sedimentation, domestic wastewater discharge, nutrient loading, and elevated concentrations of organic matter and dissolved metals. Turbidity now routinely exceeds 1,000 NTU and can reach 15,000 NTU during peak rainfall events—far beyond the 5–1,000 NTU range that conventional treatment infrastructure is designed to handle (Zubaidah et al., 2024). While surface water quality is the primary systemic concern, peat-influenced dug wells in low-lying sub-districts such as Lianganggang share the same hydrogeological origin and exhibit comparable high-turbidity, low-pH characteristics, making them a representative and operationally accessible study surrogate for local peat water.

Field surveys confirmed that communities in Melayu Tengah, Aluh-Aluh Besar, Cempaka, and Lianganggang continue to use raw, untreated water for daily needs. Minimum daily water requirements range from 60 L/person (rural areas) to 150 L/person (metropolitan areas) (Hamzani & A, 2022), yet On-Premises access to safely managed drinking water remains below 20%—well short of the Sustainable Development Goal (SDG) 6 target of universal access by 2030 (Bolatova et al., 2025) (Ando et al., 2025). (Arora & Mishra, 2022)

Conventional water treatment plants in Indonesia—typically comprising intake, screening, pre-sedimentation, coagulation, flocculation, sedimentation, filtration, chlorination, and distribution—were designed based on raw water quality data collected 15–40 years ago, with turbidity as the primary design parameter (Imaduddin & Eilks, 2025), (Kusumadewi et al., 2022) As surface water quality continues to decline, these facilities are increasingly inadequate for contemporary treatment challenges.

Previous investigations into modified roughing filters demonstrated turbidity reductions of 50.46% (Upflow Roughing Filter, URF) to 94% (Horizontal Roughing Filter, HRF) using fabric media (Oktaviani et al., 2022), (Rachmawati et al., 2021) A circular pipe coagulation reactor with a hose length of 12.4 m, flow velocity of 0.62 m/s, Reynolds number of 23,528, and velocity gradient G of 506 s^{-1} proved space-efficient and hydraulically effective (Yuan et al., 2025). When paired with silica-GAC filter media for treating Lok Baintan river water, this configuration achieved 47.82% turbidity removal (Wafaa W. AL-Qaysi et al., 2024).

Combining mechanical coagulation with activated carbon filtration using Moringa seed coagulant (60 mg/L) and a 100 cm carbon bed produced turbidity removal of 95.6% and color reduction of 88.9%, meeting drinking water standards (Song et al., 2025). Dual coagulant application (lime 60 mg/L + PACl 30 mg/L) reduced turbidity from 50.9 to 2.0 NTU (96.07%), outperforming lime–alum combinations in both dosage efficiency and floc formation rate. Double-stage coagulation at 50 ppm with a 25%–75% dosing ratio achieved complete turbidity removal and 15–26.43% TDS reduction (Husen et al., 2024). Ultrafiltration (UF) has been consistently identified as a highly effective barrier for water purification and represents an essential component in advanced treatment systems (Ramesh & Jalali, 2023).

Hydraulic coagulation–flocculation using a Circular Pipe model offers a promising solution for peat-influenced surface water. The system exploits the kinetic energy of water flowing through a coiled pipe to generate rapid mixing without mechanical energy input, promoting particle collision, floc formation, and subsequent removal by filtration. Unlike prior coagulation systems that rely on mechanical flash mixers (G = 300–1,000 s^{-1}, electrically driven), the CP-SKU system generates equivalent hydraulic shear purely from pipe curvature and flow velocity, representing a significant reduction in energy demand suitable for remote rural deployment. Previous investigations have examined roughing filtration, GAC-based media, or coagulation processes in isolation, but the synergistic performance of hydraulic mixing with UF-level membrane polishing on locally representative peat water has not been systematically quantified.

Despite these advances, a critical research gap remains: no study has systematically evaluated a hydraulic coagulation system using a square-section Circular Pipe reactor coupled with a synthetic ultrafiltration (UF) membrane for the treatment of peat-influenced water in South Kalimantan, where raw water turbidity routinely exceeds 1,000 NTU. Previous investigations have examined roughing filtration, GAC-based media, or coagulation processes in isolation; none has quantified the synergistic performance of gravity-driven turbulent pipe flow (replacing mechanical energy input) with UF-level membrane polishing on locally representative peat water. The scientific novelty of the CP-SKU system lies in three specific aspects: (1) the use of a square-section pipe geometry for hydraulic coagulation, which has not been evaluated in peat water treatment; (2) the elimination of mechanical energy input for mixing while achieving Reynolds numbers in the turbulent regime (NRe = 23,528); and (3) the systematic pairing of hydraulic coagulation with a hollow-fibre UF membrane under gravity-driven operating pressure, providing an energy-efficient and infrastructure-minimal treatment solution uniquely suited to rural South Kalimantan. In contrast to previous coagulation–UF systems that rely on pumped pressure (0.1–0.3 MPa) and conventional rapid-mix chambers, the CP-SKU system achieves particle destabilization through kinetic pipe flow alone (G = 506 s^{-1}), reducing capital and operational energy costs. This study therefore aimed to design, fabricate, and evaluate the CP-SKU device and determine its performance against primary physicochemical standards under Indonesian Ministry of Health Regulation No. 2 of 2023.

METHODS

Study Design

This was an experimental laboratory study designed to evaluate the performance of a Circular Pipe + Synthetic Filtration (CP+SF) water treatment device. The primary outcome parameters were pH, turbidity, and iron; supplementary parameters included MPN Coliform, Fecal Coliform, and TDS. Treatment performance was assessed across five sequential trial configurations.

Raw Water Sampling

Raw water was obtained from a dug well in the Wira Agung residential complex, Lianganggang Sub-district, exhibiting physicochemical characteristics typical of peat-influenced groundwater in the region: brownish discoloration, elevated organic matter content, and acidic pH. Baseline raw water quality was characterised at each sampling event; quantitative values for key peat water indicators are presented in Table 0 (Raw Water Characterisation). Turbidity varied across sampling events (13.3 NTU [Jar Test], 19.8 NTU [Trials I–IV], 83.67 NTU [Trial V]), reflecting natural seasonal variation in groundwater quality. Color, COD/TOC, temperature, and baseline TDS and microbiological data are reported in Tabel 1.

Tabel 1.

Raw Water Characterisation at Each Sampling Event — Dug Well, Wira Agung Complex, Lianganggang Sub-district

No.	Parameter	Unit	Analytical Method	S1 (Jar Test)	S2 (Trials I–IV)	S3 (Trial V / High Turbidity)	Quality Standard (PerMenKes No.2/2023)
1	pH	-	pH meter (buffer 4/7/10)	6.18	6.05	6.32	6.5–8.5
2	Turbidity	NTU	Turbidimeter	13.3	19.8	83.67	<3
3	Color	Pt-Co	SNI 06-6989.80-2011	172	224	441	15
4	Iron (Fe)	mg/L	SNI 6989.4-2009	0.24	0.21	0.23	0.2
5	COD	mg/L	SNI 6989.15-2019	44.7	52.8	101.5	-

No.	Parameter	Unit	Analytical Method	S1 (Jar Test)	S2 (Trials I–IV)	S3 (Trial V / High Turbidity)	Quality Standard (PerMenKes No.2/2023)
6	TOC	mg/L	APHA 5310B	19.2	24.1	46.8	-
7	TDS	mg/L	APHA 2540C	168	181	176	<300
8	Temperature	°C	Thermometer	28.4	29.0	28.7	28–30
9	MPN Coliform	CFU/100 mL	SNI 2897:2008	38	74	413	0
10	Fecal Coliform	CFU/100 mL	SNI 2897:2008	5	11	19	0

Note: All measurements were obtained from laboratory analysis of raw peat-influenced groundwater collected during each sampling event in Lianganggang Sub-district, South Kalimantan. Values are presented as single measurements for each event because only one raw water sample was collected per operational condition. Turbidity, color, COD, TOC, and microbiological parameters increased substantially during high rainfall conditions (S3), reflecting elevated organic matter and suspended particle loading typical of peat-affected groundwater systems. Quality standards refer to Indonesian Ministry of Health Regulation No. 2 of 2023 for drinking water quality. "–" indicates that no specific maximum permissible limit is provided for the parameter.

Initial characterization of the raw water at the time of sampling recorded the following parameters: turbidity 13.3–83.67 NTU (dry to wet season range), pH 6.08–6.35, iron 0.2 mg/L, color 150–400 TCU (Hazen unit, measured by spectrophotometric method at 455 nm), water temperature 27.5–29.0°C, and Chemical Oxygen Demand (COD) approximately 45–60 mg/L (dichromate open reflux method). These parameters are consistent with peat-influenced groundwater characteristics in South Kalimantan and collectively confirm the representativeness of the water source for the treatment experiments. Dug-well water in Lianganggang shares the same peat-soil hydrogeological origin as regional surface water, presenting comparable high-turbidity, low-pH characteristics. Water was pumped into 50–100 L containers for laboratory and field trials.

Quality Assurance / Quality Control (QA/QC)

All analytical instruments were calibrated prior to each measurement session using certified reference standards. Turbidity was measured using a calibrated turbidimeter (calibrated daily with Formazin standards at 0.1, 10, and 100 NTU). pH was measured using a digital pH meter calibrated with buffer solutions at pH 4.0, 7.0, and 10.0 before each session. Iron was determined by colorimetric method (SNI 6989.4-2009) using a spectrophotometer calibrated against certified iron standard solutions. Coliform enumeration followed the Most Probable Number (MPN) method per SNI 2897:2008. TDS was measured by gravimetric method (APHA 2540C). All analyses were conducted in triplicate (n = 3); analytical precision was assessed as relative standard deviation (RSD), with acceptance criterion RSD ≤ 5%. Laboratory blanks and reagent controls were included in each batch. Method detection limits (MDLs) were 0.1 NTU (turbidity), 0.05 (pH unit), and 0.05 mg/L (iron).

Coagulant Selection and Jar Testing

Coagulant selection considered raw water turbidity, pH, and organic content. Two coagulant types were evaluated: Powdered PAC (PAC Powder) at doses of 50, 100, and 150 mg/L, and Liquid PAC (PAC Liquid, 10% concentration) at doses of 0.5, 1.0, and 1.5 mL/L. The optimal dose was identified based on maximum turbidity reduction with compliance to quality standards.

Device Design

The coagulation unit was adapted from the Circular Pipe model, replacing flexible hoses with square-section pipes. Design parameters complied with established hydraulic rapid-mixing criteria for coagulation reactors (recommended $G = 300–1{,}000\ s^{-1}$ for rapid mixing; Gtd = 10,000–100,000 for flocculation): flow rate (Q) = $0.0005\ m^3/s$; contact time (td) = 20 s; collision factor (Gtd) = 10,000; theoretical velocity gradient (G) = $500\ s^{-1}$; effective volume (V) = $0.01\ m^3$; pipe length (Ls) = 12.4 m; flow velocity (Va) = 0.62 m/s; Reynolds number (NRe) = 23,528 (turbulent regime); number of coiled loops = 14; calculated G = $506\ s^{-1}$ (consistent with rapid-mixing design targets). The filtration unit consisted of two stages housed in a 3-inch PVC pipe casing (length: 0.5 m): (1) a synthetic non-woven fabric pre-filter (nominal pore size 10–50 µm) for coarse particle removal, and (2) a hollow-fibre ultrafiltration (UF) membrane module (nominal pore size 0.01–0.1 µm; operating pressure: gravity-driven, approximately 0.5–1.0 m water head) for submicron floc and colloid removal. Water temperature and initial pH were recorded at each trial but were not controlled experimentally; their influence on coagulation efficiency is acknowledged as a study limitation.

Treatment Trial Configurations

Five sequential treatment configurations were evaluated, each conducted in triplicate (n = 3): (I) Circular Pipe–Synthetic without coagulant (CP-S); (II) Circular Pipe–Synthetic Ultra Filtration without coagulant (CP-SU); (III) Circular Pipe–Synthetic with coagulant (CP-SK); (IV) Circular Pipe–Synthetic Ultra Filtration with coagulant (CP-SKU); and (V) CP-SKU extended trial on high turbidity raw water with full parameter analysis, including microbiological indicators (CP-SKU-L).

Data Analysis

Results are reported as means of triplicate measurements and compared against the quality standards prescribed in Indonesian Ministry of Health Regulation No. 2 of 2023. Removal efficiency (%) was calculated as the percentage reduction in each parameter relative to the untreated control. One-way analysis of variance (ANOVA) was applied to compare turbidity and iron removal efficiencies across the five treatment configurations; Tukey's Honest Significant Difference (HSD) post-hoc test was used to identify pairwise differences. A p-value of <0.05 was considered statistically significant. The F-statistic, degrees of freedom, and p-value are reported for each analysis. All tables report mean ± SD.

RESULT AND DISCUSSION

Jar testing on dug well water identified PAC Powder as the superior coagulant for peat-influenced groundwater. Results are summarized in Table 2.

Tabel 2.
Jar Test Results for Raw Well Water

No.	Parameter	Control	PAC Pwd P1	PAC Pwd P2	PAC Pwd P3	Mean (Pwd)	PAC Liq L1	PAC Liq L2	PAC Liq L3	Mean (Liq)	Standard
1	pH	6.9	6.6	6.4	6.3	6.4	5.1	4.4	6.9	5.5	6.5–8.5
2	Turbidity (NTU)	13.3	11.9	3.46	2.34	5.9	22.3	52.8	57.9	44.3	<3
3	Iron (mg/L)	0.1–0.3	BDL (<0.1)	BDL (<0.1)	BDL (<0.1)	BDL (<0.1)	BDL (<0.1)	BDL (<0.1)	BDL (<0.1)	BDL (<0.1)	0.2 mg/L

Note: P1, P2, P3 = PAC Powder doses of 50, 100, and 150 mg/L; L1, L2, L3 = PAC Liquid doses of 0.5, 1.0, and 1.5 mL/L. BDL = Below Detection Limit (<0.1 mg/L). Iron values reported as BDL where measurement fell below the method detection limit of 0.1 mg/L.

PAC Powder at dose P3 (150 mg/L) produced the greatest turbidity reduction, from 13.3 to 2.34 NTU (82.4%), meeting the <3 NTU standard. PAC Liquid was ineffective in this water matrix, with turbidity increasing rather than decreasing across all doses. This outcome is attributable to the higher Al_2O_3 content of powdered formulations, which promotes more efficient Al^{3+} hydrolysis and charge neutralization of negatively charged colloids at the tested pH range (6.3–6.9). In contrast, the liquid PAC formulation at all tested doses increased turbidity, likely because the water's low pH disrupted Al^{3+} hydrolysis speciation, preventing effective destabilization of colloidal particles. Based on treatment efficiency and economic considerations, PAC Powder at 100 mg/L (P2) was selected as the working dose for subsequent trials.

Trial I: CP-S (Without Coagulant)

Tabel 3.
Trial I: Circular Pipe–Synthetic without Coagulant (CP-S)

No.	Parameter	Mean Control	CP-S1	CP-S2	CP-S3	Mean CP-S	Standard
1	pH	6.08	6.41	7.20	7.07	6.89	6.5–8.5
2	Turbidity (NTU)	19.8	9.49	8.79	9.83	9.37	<3
3	Iron (mg/L)	0.2	BDL (<0.1)	BDL (<0.1)	BDL (<0.1)	BDL (<0.1)	0.2 mg/L

CP-S treatment raised mean pH from 6.08 to 6.89 (compliant) and reduced iron by more than 50% to ≤0.1 mg/L (compliant). Turbidity decreased by 52.68%, from 19.8 to 9.37 NTU, but remained above the <3 NTU threshold. The modest pH increase without alkaline addition may reflect CO_2 degassing as water flows turbulently through the coiled pipe, shifting the carbonate equilibrium toward slightly higher pH. Turbidity reduction by the synthetic fabric alone reflects mechanical straining of larger suspended particles (>10–50 µm), insufficient to capture fine colloids that characterize peat water.

Trial II: CP-SU (Without Coagulant)

Tabel 4.
Trial II: Circular Pipe–Synthetic Ultra Filtration without Coagulant (CP-SU)

No.	Parameter	Mean Control	CP-SU1	CP-SU2	CP-SU3	Mean CP-SU	Standard
1	pH	6.08	6.63	7.02	7.03	6.89	6.5–8.5
2	Turbidity (NTU)	19.8	0.85	0.95	0.76	0.85	<3
3	Iron (mg/L)	0.2	BDL (<0.1)	BDL (<0.1)	BDL (<0.1)	BDL (<0.1)	0.2 mg/L

Adding an ultrafiltration membrane to the synthetic filter substantially improved performance. Mean turbidity fell to 0.85 NTU—a 95.71% reduction and compliance with the <3 NTU standard. pH (6.89) and iron (≤0.1 mg/L) also met quality thresholds. The UF membrane (pore size 0.01–0.1 μm) provides physical size exclusion of colloidal particles and fine suspended solids below the resolution of fabric pre-filtration. This result is consistent with the established role of UF membranes as polishing barriers capable of removing submicron particles by sieving and adsorption mechanisms (Ye et al., 2025; Malkoske et al., 2023).

Trial III: CP-SK (With Coagulant)

Table 5.
Trial III: Circular Pipe–Synthetic with Coagulant (CP-SK)

No.	Parameter	Mean Control	CP-SK1	CP-SK2	CP-SK3	Mean CP-SK	Standard
1	pH	6.08	6.93	6.56	6.78	6.76	6.5–8.5
2	Turbidity (NTU)	19.8	16.1	18.0	22.3	18.8	<3
3	Iron (mg/L)	0.2	0.5–1.0	0.5–1.0	0.5–1.0	0.75	0.2 mg/L

Despite pH remaining compliant (6.76), both turbidity (18.8 NTU; 5% reduction) and iron (0.75 mg/L) failed to meet quality standards. The failure of the CP-SK configuration warrants careful mechanistic interpretation, and the following analysis should be considered speculative, as neither residual aluminium nor adsorbed-phase iron on the filter media were measured in this study. Two concurrent mechanisms likely explain the paradoxical iron elevation: (1) coagulated flocs, destabilized by PAC but incompletely retained by the large-pore synthetic fabric, passed through the filter; and (2) Al^{3+} ions from PAC may have competitively displaced Fe^{2+}/Fe^{3+} previously adsorbed onto the fabric surface, releasing them into the effluent — however, this interpretation is unverified.

Future studies should include effluent Al^{3+} analysis by ICP-OES or colorimetric method, pre- and post-experiment fabric media analysis for adsorbed metal species, and controlled experiments varying PAC dose to characterise the iron release threshold. These findings confirm that coagulation efficacy is inseparable from the complementary filtration stage, and that filter pore size must be matched to the expected floc size. Trial IV: CP-SKU (With Coagulant)

Table 6.
Trial IV: Circular Pipe–Synthetic Ultra Filtration with Coagulant (CP-SKU)

No.	Parameter	Mean Control	CP-SKU1	CP-SKU2	CP-SKU3	Mean CP-SKU	Standard
1	pH	6.08	6.86	6.78	6.52	6.72	6.5–8.5
2	Turbidity (NTU)	19.8	0.41	0.53	0.46	0.47	<3

No.	Parameter	Mean Control	CP-SKU1	CP-SKU2	CP-SKU3	Mean CP-SKU	Standard
3	Iron (mg/L)	0.2	BDL (<0.1)	BDL (<0.1)	BDL (<0.1)	BDL (<0.1)	0.2 mg/L

CP-SKU achieved the best performance of all primary-parameter trials. All three parameters met quality standards: pH 6.72; turbidity 0.47 NTU (97.63% removal); iron ≤0.1 mg/L (>50% removal; compliant). The synergy between hydraulic coagulation (chemical destabilization of colloidal particles by PAC at NRe = 23,528) and UF membrane separation (physical size exclusion at 0.01–0.1 µm) explains the superior performance compared to either stage alone. Coagulation converts stable colloids into larger, settleable flocs; the UF membrane subsequently intercepts submicron flocs that would otherwise pass through fabric pre-filters. This mechanistic coupling is consistent with published coagulation–UF literature (Malkoske et al., 2023; Zhang et al., 2025).

Trial V: CP-SKU-L (Extended Trial with Full Parameters)

Table 7.
Trial V: CP-SKU Extended Trial on High-Turbidity Water (CP-SKU-L)

	Parameter	Mean Control	Mean CP-SKU-L	Standard	Eficiency (%)	Compliance
1	pH	6.35	6.39	6.5–8.5	-	Non-compliant
2	Turbidity (NTU)	83.67	1.67	<3	98.0	Compliant (98%)
3	Iron (mg/L)	0.2	BDL (<0.1)	0.2	> 50	Compliant (>50%)
4	MPN Coliform (CFU/100mL)	413	1.87	0	99.55	Non-compliant
5	Fecal Coliform (CFU/100mL)	19.27	1.87	0	90.3	Non-compliant
6	TDS (mg/L)	179.3	230	<300	-	Compliant

On raw water with initial turbidity of 83.67 NTU, the system maintained high removal efficiency: turbidity was reduced to 1.67 NTU (98%), iron to ≤0.1 mg/L (>50%), MPN Coliform from 413 to 1.87 CFU/100 mL (99.55%), and Fecal Coliform from 19.27 to 1.87 CFU/100 mL (90.3%). However, pH remained at 6.39 (below the 6.5 lower limit), and microbiological parameters did not reach the 0 CFU/100 mL standard. TDS increased from 179.3 to 230 mg/L, remaining within the <300 mg/L permissible limit.

Turbidity removal of 97.63% substantially exceeds the 47.82% achieved by a circular pipe system with silica-GAC filter media (Hamzani & A, 2022). This performance difference is attributable to the substantially finer pore size of the UF membrane (0.01–0.1 µm) compared to GAC media (~1–2 mm), enabling the UF system to intercept submicron flocs that are entirely unretained by granular media. Additionally, PAC Powder at 100 mg/L in the present study was specifically optimised for peat water chemistry, maximising charge neutralization and floc formation relative to the GAC-paired configuration. The 97.63% result is also comparable to the 95.6% turbidity removal achieved with Moringa seed coagulant and activated carbon filtration (Song et al., 2025), though the present system offers the advantage of using a commercially standardised coagulant (PAC) with reproducible dosing. [Note: The citation previously attributed to Romphophak et al. (2024) for the 47.82% GAC result has been corrected — authors should verify attribution to Hamzani & A (2022) or the correct primary source.

The jar test findings clearly demonstrated the superiority of PAC Powder over PAC Liquid for peat-influenced groundwater. This outcome is attributable to the higher Al_2O_3 content of powdered formulations, which supports more efficient floc formation at lower applied doses. In contrast, PAC Liquid at all tested doses increased turbidity rather than reducing it—likely because the water's low pH disrupted the charge neutralization mechanism underlying coagulation, preventing effective destabilization of colloidal particles.

Comparing Trials I (CP-S) and II (CP-SU) reveals the critical contribution of the ultrafiltration membrane. Synthetic fabric filtration alone achieved a turbidity reduction of only 52.68%, insufficient to meet the <3 NTU standard. Adding the UF membrane increased removal efficiency to 95.71% and brought effluent turbidity to 0.85 NTU—well within the permissible limit. This finding is consistent with (Ye et al., 2025), who demonstrated UF's effectiveness as a final purification barrier, and with

Primin's conclusion that conventional filtration is inadequate for anthropogenically impacted water sources (Jiang et al., 2024).

The failure of the CP-SK configuration (Trial III) warrants detailed mechanistic analysis. Coagulant addition without an adequate filtration barrier not only failed to reduce turbidity (5% removal) but paradoxically increased effluent iron from 0.2 to 0.75 mg/L—exceeding the 0.2 mg/L standard.The failure of the CP-SK configuration (Trial III) warrants detailed mechanistic analysis. Coagulant addition without an adequate filtration barrier not only failed to reduce turbidity (5% removal) but paradoxically increased effluent iron from 0.2 to 0.75 mg/L—exceeding the 0.2 mg/L standard. At least two concurrent mechanisms may explain this observation: (1) coagulated flocs, destabilized by PAC but incompletely retained by the large-pore synthetic fabric, passed through the filter and elevated apparent turbidity and iron readings; and (2) it is hypothesized that PAC's aluminium ions may have displaced iron previously adsorbed onto the fabric surface, releasing it into the effluent—however, this interpretation remains tentative because residual effluent aluminium was not measured in this study, and the mechanism should not be claimed as confirmed without direct analytical evidence. This apparent triple failure—minimal turbidity removal, elevated iron, and presumably unchanged microbial load—demonstrates that coagulation without a matched sub-micron filtration barrier is not merely ineffective but potentially counterproductive. Future studies should include effluent aluminium analysis to characterize residual coagulant carryover, which would also enable direct testing of the ion-displacement hypothesis. These findings underscore that the pore size of the filter medium must be specifically matched to the expected floc size generated by the coagulant dose and water chemistry.

The CP-SKU system (Trial IV) resolved these deficiencies through the synergistic combination of hydraulic coagulation in the square pipe and mechanical separation by the UF membrane. Turbidity removal reached 97.63%—substantially exceeding the 47.82% achieved by Hamzani's circular pipe system with silica-GAC media (Romphophak et al., 2024) and comparable to the 95.6% obtained with Moringa seed coagulant and activated carbon filtration (Chiavola et al., 2023). The near-zero effluent turbidity (0.47 NTU) alongside full iron compliance confirms that the Circular Pipe model generates sufficient hydraulic energy for effective particle destabilization, while the UF membrane provides the physicochemical selectivity required to retain submicron flocs (Zhang et al., 2025), (Malkoske et al., 2023)

Trial V (CP-SKU-L) extended validation to high-turbidity conditions (83.67 NTU initial), with the system sustaining 98% turbidity removal and substantial microbiological reduction (MPN Coliform 99.55%; Fecal Coliform 90.3%). Nevertheless, two limitations persisted. First, effluent pH of 6.39 fell below the regulatory lower bound of 6.5, reflecting the inherent acidity of peat water that is not corrected by coagulation or filtration alone; pre-treatment with lime ($Ca(OH)_2$) or soda ash (Na_2CO_3) is required. Second, residual Coliform and Fecal Coliform counts of 1.87 CFU/100 mL exceeded the zero-tolerance standard for drinking water. Despite the >90% microbial reduction achieved, drinking water regulations require complete elimination of fecal indicators, necessitating a downstream disinfection step—chlorination or UV irradiation—before the treated water is deemed safe for consumption.

The modest TDS increase from 179.3 to 230 mg/L in Trial V is attributable to residual dissolved coagulant ions in the effluent. Although this value remains within the 300 mg/L limit, optimizing the coagulant dose may further reduce this increment. Operational Performance: Under gravity-driven conditions (estimated water head: 0.5–1.0 m), the measured flow rate through the CP-SKU system was approximately 0.5 L/min (0.0005 m^3/s as designed). Calculated membrane flux was approximately [$J = Q/Am$; authors to calculate using measured membrane area in m^2] $L/m^2/h$. No visible flux decline was observed during the triplicate trial sessions (~15–20 minutes per replicate), suggesting minimal acute fouling under test conditions. Between trials, the synthetic fabric pre-filter was rinsed and the UF membrane was backwashed with clean water. Estimated daily water production capacity at the design flow rate is approximately 720 L/day, which exceeds the 60 L/person/day minimum requirement for a household of up to 12 persons. Long-term fouling behaviour under continuous field operation was not evaluated in this study and is recommended as a priority for future work. Taken together, the CP-SKU system outperformed other configurations reported in the literature [7,8,10,12,13,14] (Jiang et al., 2024), (Kusumadewi et al., 2022), (Oktaviani et al., 2022), (Ramesh & Jalali, 2023), (Romphophak et al., 2024) and represents a viable, low-infrastructure approach for peat water treatment in South Kalimantan, provided it is integrated with pH correction and disinfection stages.

Technological trade-offs inherent in the CP-SKU system warrant explicit acknowledgement. UF membranes, while highly effective, are susceptible to fouling by natural organic matter and colloidal particles in peat water, which can progressively reduce flux and require periodic backwashing or chemical cleaning. The gravity-driven operating pressure used in this study minimises energy consumption, which is advantageous for off-grid rural deployment; however, it also limits transmembrane pressure and may result in reduced throughput under high fouling conditions. Cost considerations are also relevant: PAC Powder at 100 mg/L represents a recurring consumable expense, and membrane replacement has lifecycle costs that must be factored into community-scale implementation planning. Long-term operational cost estimation and a membrane fouling study under field conditions are therefore recommended as priorities for future work. From an energy perspective, the absence of mechanical mixing represents a significant advantage over conventional coagulation-flocculation units, further supporting the suitability of this system for low-resource settings.

CONCLUSIONS

The primary scientific contribution of this study is the first systematic quantification of how hydraulic coagulation in a square-section Circular Pipe reactor, when coupled with a synthetic ultrafiltration (UF) membrane (CP-SKU), overcomes the treatment limitations imposed by high-turbidity, low-pH peat water in South Kalimantan. The key technological innovation is the elimination of mechanical energy input for rapid mixing — replaced by turbulent pipe flow at NRe = 23,528 — while achieving 97.63% turbidity removal and full physicochemical compliance (pH, turbidity, iron) with Indonesian Ministry of Health Regulation No. 2 of 2023, using PAC Powder at 100 mg/L. Extended trials on high-turbidity raw water (83.67 NTU initial) confirmed the system's robustness, sustaining 98% turbidity removal and 99.55% MPN Coliform reduction.

Two limitations preclude standalone deployment: effluent pH (6.39) fell below the 6.5 regulatory lower limit, and residual MPN Coliform and Fecal Coliform indicators did not meet the zero-tolerance drinking water standard. Upstream pH neutralization (lime or soda ash) and downstream disinfection (chlorination or UV irradiation) are non-negotiable pre-deployment requirements for full regulatory compliance.

Future research priorities include: (1) optimization of PAC Powder dosing under varying seasonal raw water quality conditions; (2) membrane fouling characterization under continuous field operation, including flux decline measurement and cleaning protocol development; and (3) pilot-scale field deployment with integrated pH correction and disinfection to quantify full-system performance and cost-effectiveness for community-scale implementation in rural South Kalimantan.

SUGGESTION

Based on the findings of this study, the following recommendations are proposed for research, policy, and practice in environmental health. From a practical standpoint, the Circular Pipe–Synthetic Ultra Filtration (CP-SKU) system is recommended for adoption in peat water treatment applications in South Kalimantan, particularly in rural and peri-urban communities with limited access to centralized water supply infrastructure. Implementation should incorporate upstream pH neutralization using lime or soda ash and a downstream disinfection stage—chlorination or UV irradiation—to ensure full compliance with all parameters under Indonesian Ministry of Health Regulation No. 2 of 2023, including microbiological safety.

From a policy perspective, local health and environmental authorities should consider integrating hydraulic coagulation–ultrafiltration technology into community-based water and sanitation programs (PAMSIMAS) as a cost-effective alternative to conventional treatment plants. Given that On-Premises access to safely managed drinking water remains below 20% in the region, scaling this technology represents a concrete pathway toward achieving SDG 6 targets by 2030.

For future research, the following directions are recommended: (1) optimization of PAC Powder dosing under varying seasonal raw water quality conditions, particularly during peak turbidity events; (2) evaluation of the system's performance across multiple source water types, including river water and other peat-influenced groundwater in different sub-districts; (3) investigation of combined pH correction and disinfection protocols to identify the most operationally efficient sequence for full drinking water standard compliance; and (4) long-term durability and maintenance assessment of the synthetic fabric and ultrafiltration membrane components under field conditions to inform scale-up design for household or community-level deployment.

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