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Original Research Article

Green Coagulation of Contaminated Groundwater Using Papaya Seed and Chicken Eggshell-Based Biocoagulants

Riana Ayu Kusumadewi[1*], Winarni[1], Nadia Amalia Cahyanigrum[2], Hanief Rifqyawarman[3], Rositayanti Hadisoebroto[1], Sheilla Megagupita Putri Marendra[1], Chandra Suryani Rahendaputri[4]

[1]Environmental Engineering Department, Faculty of Architecture Landscape and Environmental Technology, Universitas Trisakti, Jl. Kyai Tapa No. 1, Grogol, West Jakarta, DKI Jakarta, Indonesia 11440
[2]PT Air Bersih Jakarta (Moya Indonesia Group), Setiabudi Atrium, 4th Floor, Jl. H.R. Rasuna Said Kav. 62, Kuningan, Setiabudi, South Jakarta, DKI Jakarta, Indonesia 12920
[3]PT Moya Bekasi Jaya (Moya Indonesia Group), Jl. Raya Tegal Gede No. 56, Cikarang Selatan, Bekasi Regency, West Java, Indonesia 17530
[4]The University of Osaka, Graduate School of Engineering, Division of Sustainable Energy and Environmental Engineering, 2-1 Yamadaoka, Suita, Osaka, Japan
* Corresponding Author, email: rianaayu.kusumadewi@trisakti.ac.id

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Abstract

Groundwater from a public bathing, washing, and toilet facility in West Jakarta had turbidity of 70 NTU and conductivity-derived total dissolved solids (TDS) of 350 mg/L. This exploratory study evaluated papaya seed (PS) and chicken eggshell (CE) biocoagulants using jar tests followed by pilot-scale coagulation–flocculation–sedimentation–filtration. The selected nominal mixing targets were coagulation $G \cdot t_d$ of 48,000 and flocculation $G \cdot t_d$ of 28,000, with a nominal starting-material dose of 500 mg/L and 150-mesh precursor powder. Following 2 h of sedimentation and filtration, turbidity removal reached 97.04% for PS and 97.23% for CE, while calculated reductions in conductivity-derived TDS were 65.86% and 66.14%, respectively. Final TDS estimates were 119.5 and 118.5 mg/L, numerically below the <300 mg/L benchmark specified in Indonesian Ministry of Health Regulation No. 2 of 2023. Other measured physicochemical parameters were within their respective benchmark values. However, the original EC-to-TDS conversion setting could not be verified, and gravimetric validation was not performed. These findings indicate preliminary physicochemical improvement, not confirmation of safety for direct drinking. Microbiological testing, broader chemical assessment, and appropriate disinfection are required before drinking-water use can be considered.

Keywords: Chicken eggshell; coagulation; flocculation; groundwater; papaya seed; removal efficiency

1. Introduction

Groundwater remains an important water source, particularly in areas with limited centralized treatment infrastructure, but contamination by suspended solids, dissolved constituents, and microbial pollutants can restrict its use. Conventional coagulation–flocculation using aluminum or iron salts is effective for water clarification, although concerns about sludge generation, residual metals, and environmental burdens have encouraged interest in alternative coagulants (Ali, Abdou, Emara, Farag,

and Mubarak, 2025; Díaz-Martínez, Navarro-Amador, Sánchez-Salas, and Flores-Cervantes, 2025). Natural coagulants derived from renewable biological resources and agricultural waste offer potential advantages in local availability and biodegradability, but their performance and practical constraints require evaluation under relevant water-quality conditions (Diver, Nhapi, and Ruziwa, 2023; Lwasa, Mdee, Ntalikwa, and Sadiki, 2024).

Papaya seed (*Carica papaya* L.) is an agricultural by-product investigated as a source of natural coagulants. Its protein-containing fractions can contribute to colloid destabilization through charge neutralization, adsorption, and bridging, depending on preparation conditions and water chemistry (R. Putra and Airun, 2021). Protein-rich plant materials have also been investigated in natural-biocoagulant treatment applications (Fadli et al., 2024). Previous studies have evaluated papaya seed-derived coagulants, alone or in combination with other natural materials, for treating polluted water and wastewater, demonstrating their potential for turbidity reduction (Amran et al., 2021; Muhamad et al., 2024; Yimer and Dame, 2021). However, these findings do not directly establish their performance in contaminated groundwater or after transfer to pilot-scale treatment.

Chicken eggshell is another waste-derived material of interest because of its calcium-carbonate-rich mineral matrix. Eggshell-based preparations have been investigated for coagulation–flocculation applications, including microalgae harvesting (Shazili et al., 2025). Nevertheless, much of the literature emphasizes eggshell-derived adsorbents for organic and inorganic contaminant removal rather than their use as primary coagulant preparations in groundwater treatment (Manyatshe and Sibali, 2025). The contrasting composition and preparation requirements of papaya seed and chicken eggshell therefore warrant comparison under common groundwater treatment conditions without assuming equivalent active constituents or removal mechanisms.

Selection of operating conditions and evaluation beyond laboratory screening are important considerations in coagulation studies (Direstiyani and Pratama, 2025; Nguyen, Nguyen, Schmalz, and Tran, 2025). However, direct comparisons of papaya seed and chicken eggshell preparations across jar-test screening and pilot-scale groundwater treatment remain limited. This exploratory study therefore evaluated both preparations using contaminated groundwater from a bathing, washing, and toilet (BWT) facility in West Jakarta. Jar tests examined mixing conditions, nominal starting-material dosage, and precursor particle size, followed by pilot-scale coagulation–flocculation–sedimentation–filtration under selected conditions. Performance was assessed through turbidity removal, changes in conductivity-derived total dissolved solids, and selected physicochemical parameters. Indonesian drinking-water parameter values were used as comparative benchmarks, not as confirmation that the treated water was safe for direct drinking.

2. Methods

2.1 Papaya Seed and Chicken Eggshell Coagulants Preparation

Papaya seeds (*Carica papaya* L.) (PS) were obtained from fruit vendors in Jakarta. Meanwhile, chicken eggshells (CE) were obtained from cake makers and street vendors in South Tangerang. After collecting the papaya seeds and chicken eggshells, they were cleaned and soaked in hot water for approximately 15 minutes, followed by drying in an oven at 105ºC for 90 minutes (for papaya seeds) and 30 minutes (for chicken eggshells). The dried materials were ground using a mortar and pestle and sieved using 50-, 100-, and 150-mesh sieves, with nominal openings of approximately 300, 150, and 106 µm, respectively. The powdered papaya seeds and chicken eggshells were stored in a desiccator and used as a biocoagulant.

For preparation of the PS coagulant extract, 0.5 g of sieved papaya seed powder was mixed with 100 mL of 1 M NaCl solution and stirred at 100 rpm for 30 min. The mixture was subsequently filtered to separate the seed residue, and the filtrate was used as the liquid PS coagulant. This preparation corresponded to a nominal initial powder loading of 5 g/L of extraction medium. Acetic acid was not used for PS preparation. For preparation of the liquid CE coagulant, 10 g of sieved chicken eggshell powder was

mixed with 1,000 mL of 1% (v/v) acetic acid (CH_3COOH) solution and stirred at 200 rpm for 9 h. Following mixing, the final preparation volume was adjusted to 1,000 mL, corresponding to a nominal eggshell starting-material-equivalent concentration of 10 g/L. This nominal concentration was based on the initial eggshell powder mass and the final preparation volume, rather than on a measured concentration of dissolved active constituents. The entire preparation was used for dosing without a separate filtration step. Thus, different preparation media and mixing conditions were used for the two biocoagulants: NaCl solution for PS and acetic acid solution for CE. The preparation procedures are illustrated in Figure 1.

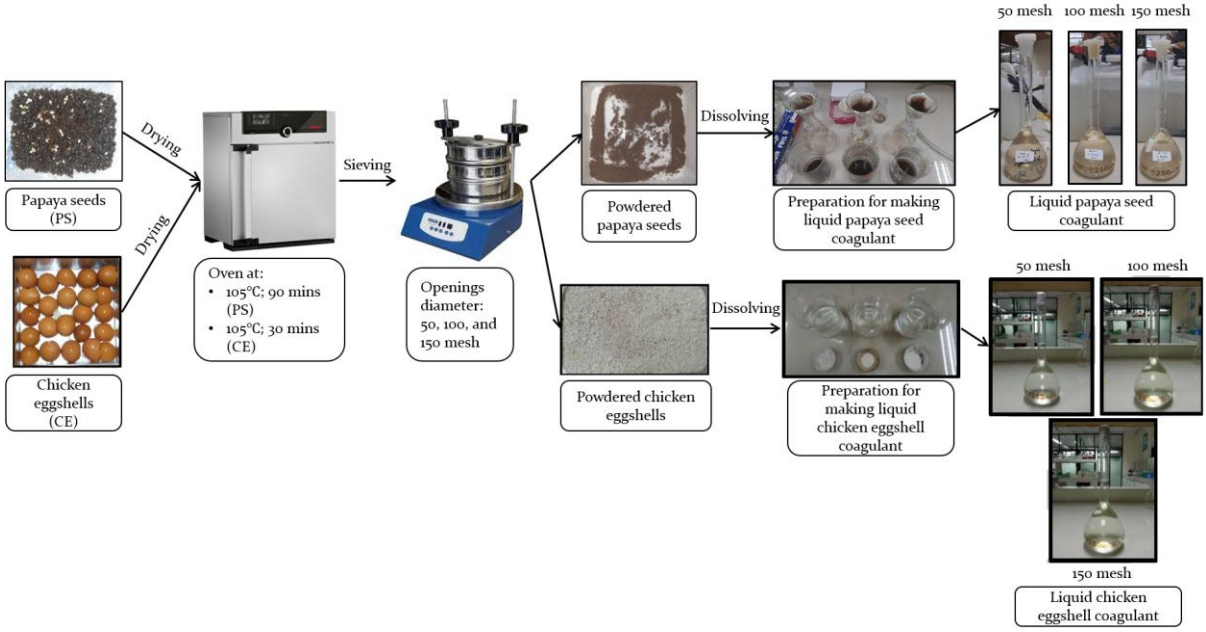


Figure 1. Preparation of papaya seed and chicken eggshell coagulants

2.2 Contaminated Groundwater

The groundwater used for the study was taken from a pump well at the Bathing, Washing, and Toilet (BWT) Facility in RW 01, Jalan Taman Bunga I/13, South Kota Bambu Village, Palmerah District, West Jakarta City, Special Capital Region of Jakarta. Raw water was taken once for use in all research variations. The obtained groundwater was then tested for quality to determine the concentration of pollutant parameters in groundwater at the Environmental Laboratory of the Environmental Engineering Study Program, Campus A, West Jakarta. The water quality parameters tested included pH, turbidity, total dissolved solids (TDS), nitrite, nitrate, iron, and manganese.

TDS was estimated from electrical conductivity (EC) using the TDS mode of an Adwa AD8000 benchtop multiparameter meter. According to the manufacturer, the AD8000 has a default EC-to-TDS conversion factor of 0.50, adjustable from 0.40 to 1.00. However, the conversion setting used during the original measurements could not be verified from the available records. Details of the EC calibration standard and temperature-compensation settings used during the original measurements could not be recovered from the available records. No gravimetric TDS determination was performed. The reported TDS values are therefore retained as conductivity-derived estimates, and the uncertainty associated with the conversion setting is acknowledged as a study limitation. Selected drinking-water parameter values from the Annex to Indonesian Ministry of Health Regulation No. 2 of 2023 (Kementerian Kesehatan Republik Indonesia, 2023) were used as comparative benchmarks for assessing treatment performance, including a TDS requirement of <300 mg/L. These comparisons do not constitute a complete assessment of drinking-water safety. In particular, TDS comparisons were based on conductivity-derived estimates without independent gravimetric validation.

2.3 Jar Test Study

Both papaya seed (PS) and chicken eggshell (CE) preparations were evaluated at nominal starting-material doses of 100–500 mg/L in 100 mg/L increments and precursor sizes of 50, 100, and 150 mesh (approximately 300, 150, and 106 µm, respectively). Mixing conditions are summarized in Table 1. Percentage reductions were calculated using Eq. (1) (Ezemagu, Ejimofor, Menkiti, and Nwobi-Okoye, 2021), with turbidity as the primary indicator of coagulation performance and conductivity-derived TDS and selected inorganic parameters used to assess additional water-quality changes.

$$\eta(\%) = \frac{C_0 - C}{C_0} \times 100\% \quad (1)$$

where η is the removal efficiency (%), C_0 is the initial concentration of the parameter in the raw groundwater, and C is the concentration after treatment.

Table 1. Mixing conditions used for jar-test screening of papaya seed and chicken eggshell coagulant preparations

Process	Mixing speed (rpm)	Mixing duration, t_d(s)	Nominal G(s^{-1})	Nominal $G.t_d$(dimensionless)	Design Reference
Coagulation	100	60	283	17,000	(Airun, 2020)
Coagulation	100	120	283	34,000	(Airun, 2020)
Coagulation	200	60	800	48,000	(Puteri, 2020)
Coagulation	200	120	800	96,000	(Puteri, 2020)
Flocculation	20	1,080	~26	28,000	(Qasim, Motley, and Zhu, 2000)
Flocculation	40	1,080	~71	77,000	(Qasim et al., 2000)

Mixing power and the mean velocity gradient were estimated using the mechanical-mixing relationships $P = N_P \rho N^3 D^5$and $G = \sqrt{P/\mu.V}$, where P is the power transferred to the liquid (W), N_p is the dimensionless impeller power number, ρ is liquid density (kg/m³), N is rotational speed (s^{-1}), D is impeller diameter (m), µ is dynamic viscosity (Pa·s), and V is the effective mixing volume (m³) (Qasim, Motley, and Zhu, 2000). Rotational speeds in rpm were divided by 60 before calculation. The product $G{\cdot}t_d$ is dimensionless, with t_d denoting mixing time in seconds.

The underlying jar-test calculation records specify V = 0.0005 m³, D = 0.09 m, N_p = 3.3, ρ = 997.1 kg/m³, and µ = 0.00089 Pa·s (Cahyaningrum, 2023; Rifqyawarman, 2023). However, recalculation using these recorded inputs does not reproduce the G values assigned to the reported rotational speeds. The G and $G{\cdot}t_d$ values in Table 1 are therefore retained as nominal design values rather than independently verified hydrodynamic estimates. The discrepancy limits exact reconstruction of the jar-test mixing intensity.

2.4 Coagulation, Flocculation, Sedimentation, and Filtration Reactors

Pilot-scale experiments were conducted at the BWT facility described in Section 2.2 using a batch coagulation–flocculation–sedimentation–filtration system. A 550-L propeller-mixer reactor was operated with 225 L of groundwater per run. Coagulant dosage, precursor particle size, and mixing conditions were selected from the jar-test results. Pilot mixing calculations used a propeller impeller with a diameter of 0.25 m, a pitch ratio of 1:1, and an adopted N_p of 0.3. The calculation volume was 0.225 m³, with ρ = 997.1 kg/m³ and µ = 0.00089 Pa·s, following the underlying experimental records (Cahyaningrum, 2023; Rifqyawarman, 2023). Using the recorded pilot-reactor assumptions, the estimated G values were approximately 232 s^{-1} at 200 rpm and 38 s^{-1} at 60 rpm. The calculated mixing times corresponding to the nominal $G{\cdot}t_d$ targets of 48,000 and 28,000 were approximately 207 and 733 s, respectively. The source

experimental descriptions report rapid and slow mixing as 200 rpm for approximately 3 min and 60 rpm for approximately 12 min; these rounded descriptions should not be interpreted as exact confirmation of the target $G \cdot t_d$ values. The jar-test values in Table 1 and the pilot-scale estimates are therefore reported separately; matching nominal $G \cdot t_d$ targets does not establish identical mixing conditions between scales.

Following coagulation and flocculation, water was allowed to settle for 1, 1.5, or 2 h and evaluated before and after filtration. The reactor layout and filtration tank are shown in Figure 2. SD1, SD1.5, and SD2 denote 1, 1.5, and 2 h of sedimentation, respectively; +FT indicates subsequent filtration. Both coagulant preparations were evaluated for turbidity, conductivity-derived TDS, nitrite, nitrate, iron, manganese, pH, and temperature. Jar-test and pilot-scale evaluations were conducted as single treatment runs using one collected groundwater batch. Each sample was measured twice, and results are reported as arithmetic means. These duplicate measurements were not independent treatment replicates; therefore, results were interpreted descriptively as exploratory findings rather than statistically replicated comparisons.

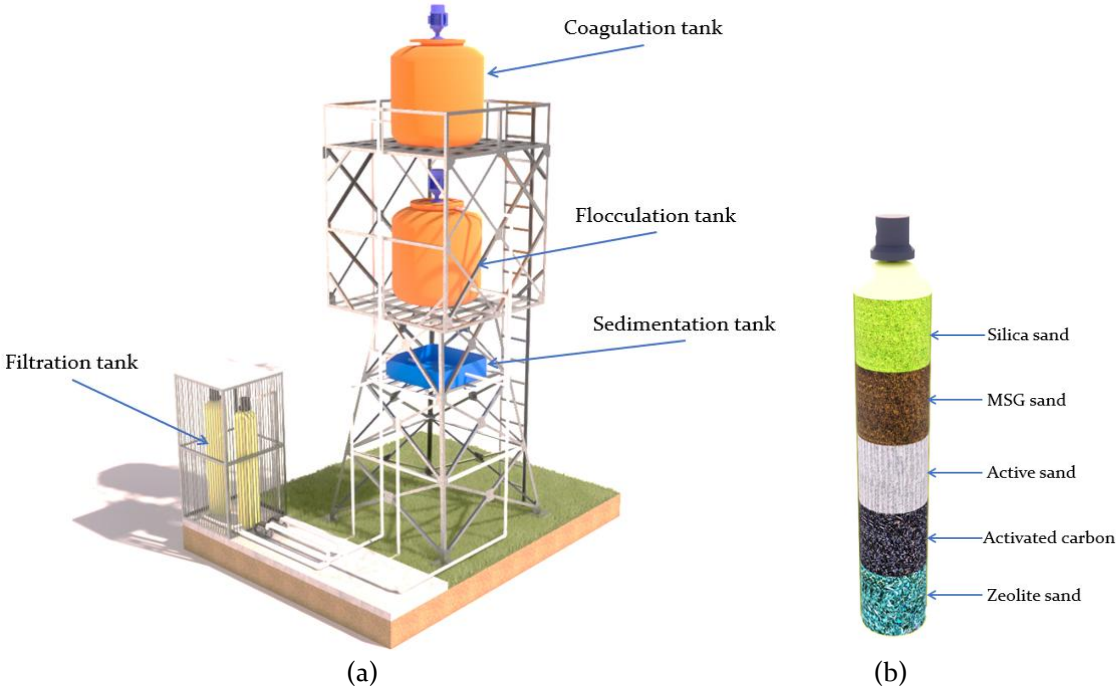


Figure 2. Design of coagulation, flocculation, sedimentation, and filtration reactors (a) and filtration tank detail (b) at the BWT facilities in South Kota Bambu Subdistrict, West Jakarta

3. Results and Discussion

3.1 Characterization of Biocoagulant Raw Materials

PS and CE precursors showed contrasting compositions (Supplementary Table S13). PS contained reported moisture, ash, and protein contents of 1.3%, 7.84%, and 60.75%, respectively, whereas CE contained 92.6% $CaCO_3$. The relatively high protein content identifies PS as a protein-rich organic precursor, while the $CaCO_3$ content indicates the predominantly mineral character of CE. These compositional differences are relevant to their preparation and potential interactions with groundwater constituents, but do not establish the concentrations or activities of the constituents ultimately dosed.

For PS, protein content provides a compositional basis for considering protein-associated coagulating constituents. Papaya-seed proteins and their functional groups have been investigated for their potential to behave as polyelectrolytes in coagulation (Amran et al., 2021). However, total precursor protein is not equivalent to the concentration of active protein in the filtered NaCl extract used here. Extraction efficiency, protein charge, and the contribution of individual constituents were not determined. Moisture describes the residual water content of the precursor, whereas ash represents the

inorganic residue remaining after combustion; neither parameter alone measures coagulating activity or the amount of dissolved material introduced during dosing. Airun (2020) reported moisture, ash, and protein contents of 7.29%, 7.55%, and 19.7%, respectively. Differences should be interpreted cautiously because sample preparation, analytical methods, and reporting bases may differ; these literature values are compositional observations, not acceptance criteria.

For CE, the measured $CaCO_3$ content of 92.6% was numerically close to the 92.57% reported by Warsy et al. (2016), supporting its description as a calcium-carbonate-rich precursor rather than demonstrating coagulant suitability. Its mineral composition also makes the preparation medium important: acid treatment can dissolve the mineral shell during eggshell-membrane separation (Park et al., 2016). The CE preparation used here should therefore not be assumed to retain the same composition or surface properties as the untreated powder. The actual dissolved fraction and the composition of the preparation after acid treatment were not quantified.

At the nominal CE dose of 500 mg/L, the precursor composition corresponds to approximately 463 mg/L of $CaCO_3$-equivalent starting material per litre of groundwater. This is not a measured dissolved concentration and cannot be assumed negligible relative to the initial conductivity-derived TDS of 350 mg/L. Neither negligible nor complete dissolution is assumed, and contributions from CE constituents and the preparation medium cannot be separated using the available measurements. Overall, the characterization distinguishes a protein-rich organic precursor from a carbonate-rich mineral precursor, while treatment performance remains an experimental outcome rather than a property inferred from composition alone.

3.2 Effects of Mixing Conditions and Dosage on Turbidity Removal and Conductivity-Derived TDS Reduction

Figure 3 presents the effects of coagulation and flocculation conditions and nominal dosage using 50-mesh precursor powder (~300 μm). For both preparations, turbidity removal generally increased with coagulation G·t_d, with diminishing improvements at higher settings. This trend is consistent with rapid mixing promoting particle contact and microfloc formation up to a practical performance plateau (Widiyanti et al., 2023). Mixing can influence clarification by increasing opportunities for particle contact, rather than merely distributing the coagulant. This role was also discussed in raw-water electrocoagulation experiments by Pradiko et al. (2018), although the different coagulant-generation process limits direct mechanistic extrapolation to PS and CE preparations. Increasing flocculation $G{\cdot}t_d$ from 28,000 to 77,000 produced smaller changes, consistent with slow mixing primarily supporting the growth of previously destabilized particles (Esteki, Ehrampoush, Nasab, and Ebrahimi, 2024). Conductivity-derived TDS showed a weaker response to mixing, consistent with coagulation–flocculation primarily targeting suspended and colloidal particles rather than the truly dissolved fraction (Ojo, 2024).

Increasing the nominal dosage from 100 to 500 mg/L generally improved turbidity removal. Greater availability of coagulating constituents may promote particle destabilization and aggregation (Minaya Gutiérrez et al., 2025). The dosage response should also be interpreted in relation to mixing conditions, since the availability of coagulating constituents alone does not determine their effective contact with particles. The combined evaluation of dosage and coagulation $G{\cdot}t_d$ in papaya-seed groundwater treatment provides a basis for considering these factors together rather than interpreting dosage effects in isolation (Cahyaningrum et al., 2024). Conductivity-derived TDS reductions changed more gradually with dosage; comparisons with other seed-based treatment studies provide context for these trends (Adrin, Ngadiman, Abdullah, and Hamdan, 2025). However, the observed changes do not establish adsorption, co-precipitation, or specific dissolved-ion removal mechanisms. They are therefore reported as reductions in conductivity-derived TDS rather than confirmed removal of dissolved-solids mass.

Nominal coagulation $G{\cdot}t_d$ of 48,000 and flocculation $G{\cdot}t_d$ of 28,000 were selected for pilot evaluation because higher tested settings did not consistently provide substantial additional

improvement across both preparations. Selection favored lower mixing requirements where additional mixing produced limited numerical gains; energy consumption was not directly measured. A nominal dose of 500 mg/L was carried forward because it generally produced higher turbidity removal within the tested range. These conditions are preliminary selections rather than a confirmed optimum because experiments used one groundwater batch and single treatment runs; duplicate measurements of each sample were not independent treatment replicates. Complete numerical results are provided in Supplementary Tables S1–S12, with representative comparisons in Supplementary Table S14.

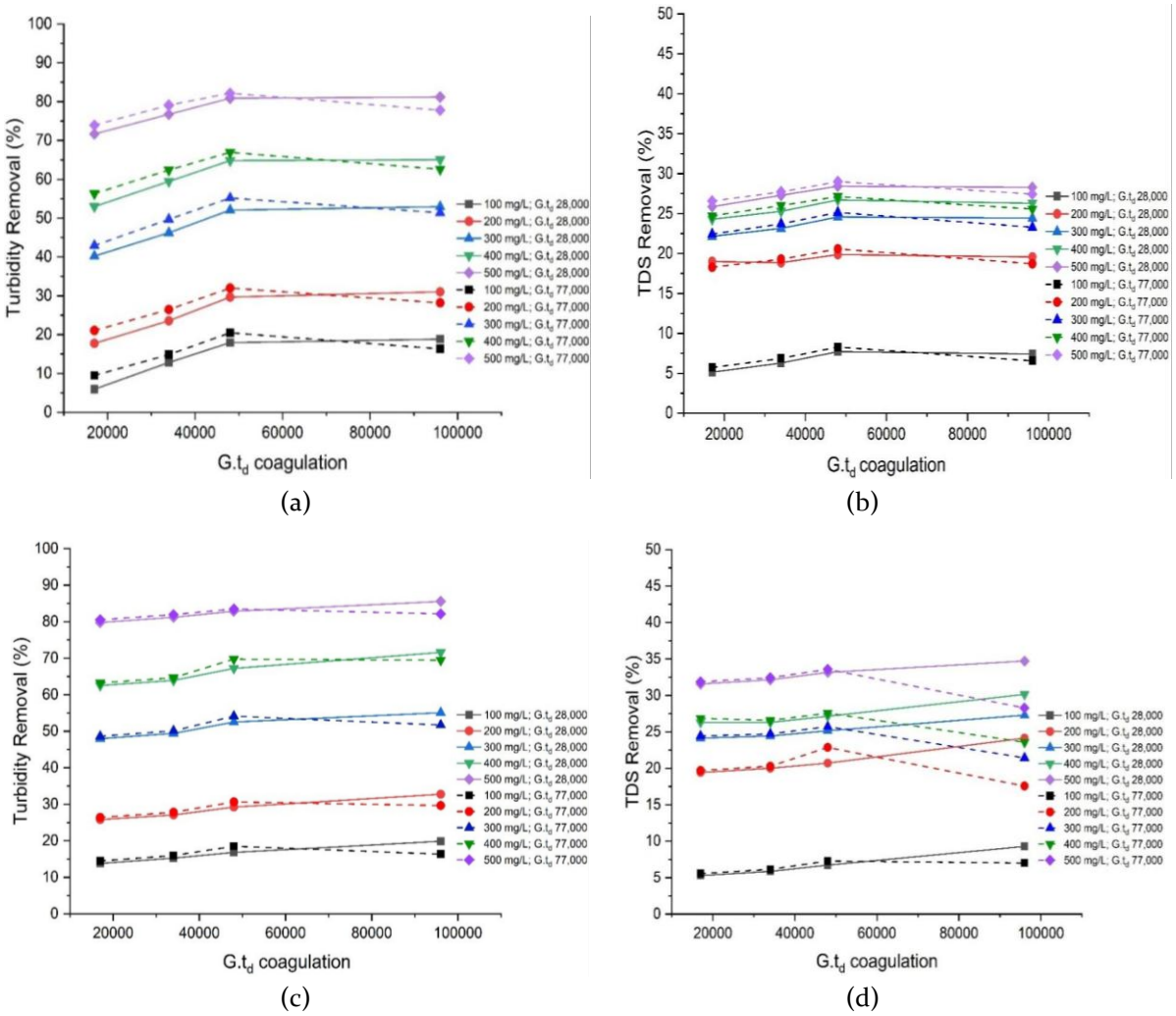


Figure 3. Effects of coagulation and flocculation conditions on turbidity removal and conductivity-derived TDS reduction using coagulant preparations from 50-mesh precursor powder (~300 µm): (a) turbidity removal using papaya seed; (b) TDS reduction using papaya seed; (c) turbidity removal using chicken eggshell; and (d) TDS reduction using chicken eggshell. Results were calculated from duplicate measurements of each sample, not independent treatment replicates.

3.3 Effect of Precursor Particle Size on Turbidity Removal and Conductivity-Derived TDS Reduction

At a flocculation G·t$_d$ of 28,000, preparations produced from 150-mesh precursor powder (~106 µm) generally achieved higher turbidity removal than those prepared from 100-mesh (~150 µm) and 50-mesh (~300 µm) powder (Figure 4). Finer grinding may increase surface accessibility and influence the availability of coagulating constituents, providing a possible explanation for this trend (Okoro, Sharifi, Jesson, and Bridgeman, 2021). Because the powders underwent liquid preparation before dosing, the observed response should be interpreted as an effect of precursor size rather than direct evidence of the

particle size of the dosed active constituents. The particle-size response reported for eggshell-based groundwater treatment indicates that precursor fineness is relevant to process performance; however, this association alone does not distinguish changes in constituent availability from subsequent particle–coagulant interactions (Rifqyawarman et al., 2024).

Conductivity-derived TDS reductions also generally increased with finer precursor size, although the response was less pronounced than for turbidity. The observed plateau does not establish adsorption-site saturation; changes in extraction, interactions with dissolved constituents, and other influences on conductivity require further investigation (Badawi, Salama, and Mostafa, 2023). The 150-mesh precursor was therefore selected for pilot evaluation based on its observed performance within the tested range, without claiming a universally optimal particle size.

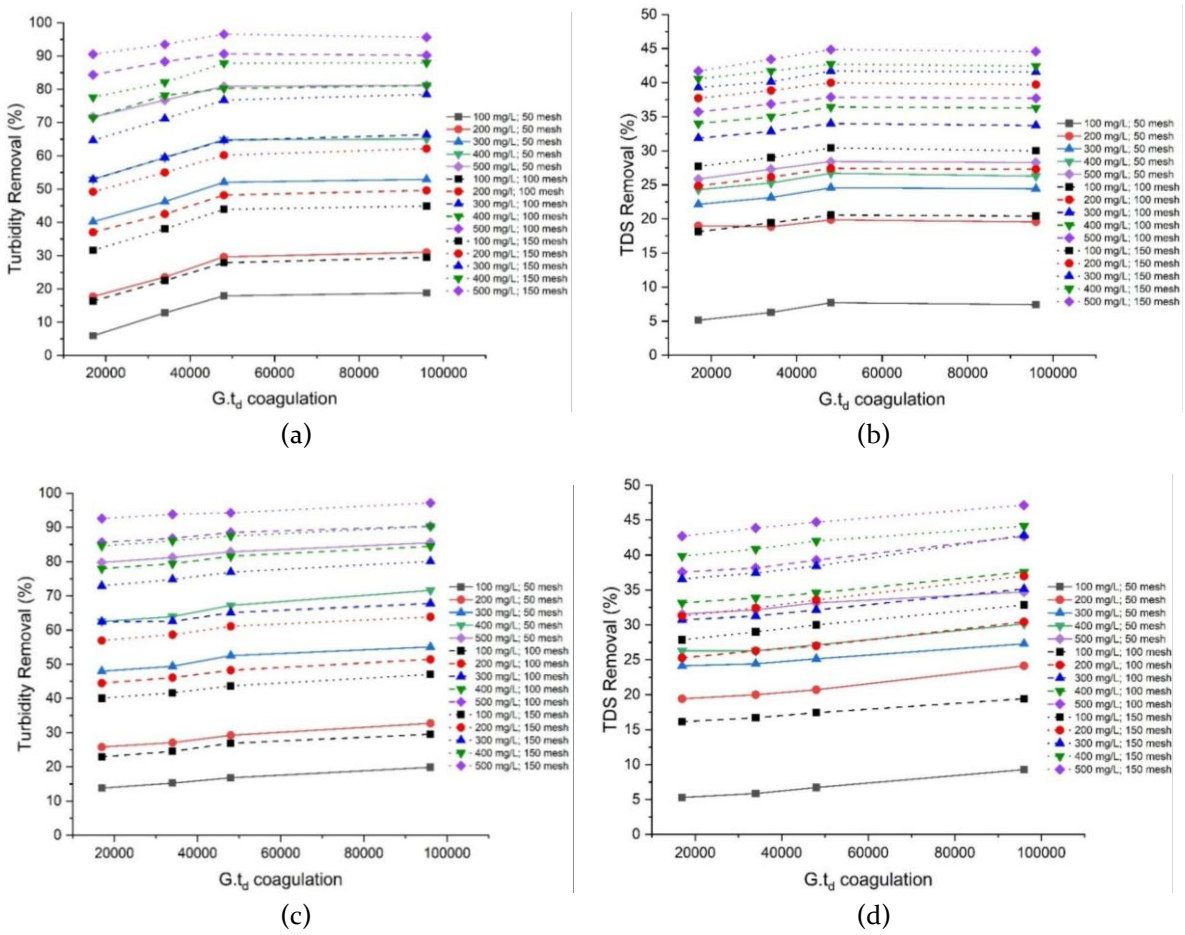


Figure 4. Effects of precursor particle size on turbidity removal and conductivity-derived TDS reduction using papaya seed and chicken eggshell coagulant preparations: (a) turbidity removal using papaya seed; (b) TDS reduction using papaya seed; (c) turbidity removal using chicken eggshell; and (d) TDS reduction using chicken eggshell. Results were calculated from duplicate measurements of each sample, not independent treatment replicates.

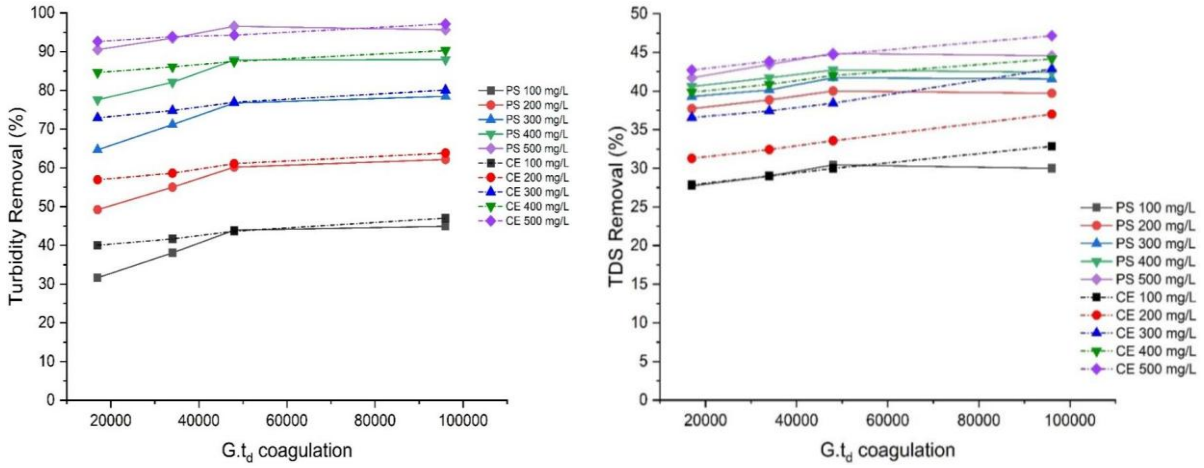
3.4 Comparison of Papaya Seed and Chicken Eggshell Treatment Performance

Figure 5 compares PS and CE at 150 mesh (~106 µm) and a flocculation G·t$_d$ of 28,000. Both preparations showed greater percentage reductions in turbidity than in conductivity-derived TDS. Their turbidity responses are consistent with the clarification potential reported for natural coagulants, although performance depends on material preparation and water characteristics (Okoro et al., 2021; Kurniawan et al., 2020). Previous studies on papaya seed preparations and eggshell-derived materials provide compositional and treatment context, but do not establish the mechanisms operating in the

present groundwater experiments (Amran et al., 2021; Ngomane, Khumalo, Mahlangu, Tetteh, and Rathilal, 2023; Manyatshe and Sibali, 2025).

At the selected condition, coagulation G·t_d of 48,000, flocculation G·t_d of 28,000, nominal dose of 500 mg/L, and 150-mesh precursor, turbidity removal was 96.54% for PS and 94.26% for CE, while conductivity-derived TDS reduction was 44.86% and 44.71%, respectively. Supplementary Table S14 presents these values alongside higher-mixing conditions to make the selection basis transparent. Increasing coagulation G·t_d to 96,000 at the same flocculation setting changed turbidity removal to 95.64% for PS and 97.17% for CE, indicating that the response to additional mixing differed between preparations.

Because the experiments used single treatment runs without independent treatment replication, these descriptive results do not establish superiority or statistical equivalence of either preparation. Differences in preparation media and constituent chemistry may influence performance, but adsorption, co-precipitation, and site saturation were not directly demonstrated. Broader groundwater-treatment literature provides context for considering such processes, not confirmation of their occurrence here (Thomas, Vinka, Pawan, and David, 2022). Independent treatment replication, preparation-medium controls, and dissolved-constituent measurements are needed to resolve the observed differences.



(a) (b)

Figure 5. Comparison of (a) turbidity and (b) conductivity-derived TDS reduction using papaya seed and chicken eggshell biocoagulants under selected jar-test conditions. Removal efficiencies were calculated from the mean concentrations obtained from two measurements of each sample; independent treatment replicates were not performed.

3.5 Groundwater Quality Testing in Pilot Scale Coagulation, Flocculation, Sedimentation and Filtration Reactors

The pilot system was evaluated using the nominal coagulation and flocculation G·t_d targets of 48,000 and 28,000 selected during jar-test screening, together with a nominal dose of 500 mg/L and 150-mesh precursor powder. Figure 6 and Table 2 summarize the outcomes at different sedimentation times, with and without filtration; treatment codes are defined in Section 2.4. Initially, turbidity (70 NTU) and conductivity-derived TDS (350 mg/L) exceeded the respective benchmarks, while manganese (0.100 mg/L) was at its limit. In contrast, pH, nitrite, nitrate, and iron were already within their respective benchmark values; their results therefore should not be presented as correction of initially non-compliant water quality.

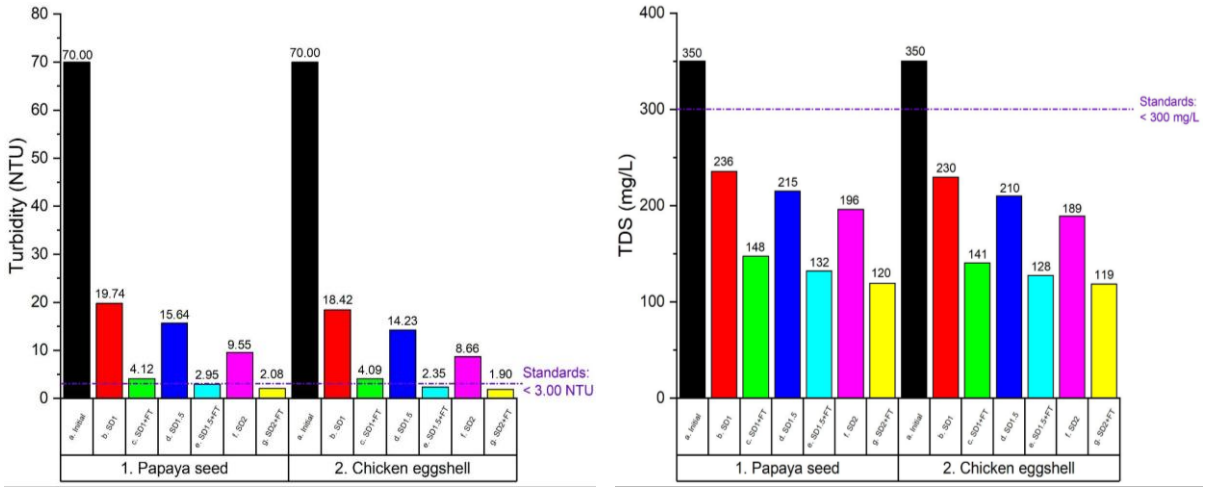
Turbidity decreased with sedimentation and declined further after filtration. At 2 h, sedimentation alone produced values of 8.66–9.55 NTU, whereas subsequent filtration reduced them to approximately 1.9–2.1 NTU, corresponding to removals of 97.04% for PS and 97.23% for CE. This pattern is consistent with sedimentation removing settleable flocs and filtration capturing remaining finer

particles (Malik, Khyalia, and Laura, 2024). Its dependence on treatment conditions and influent characteristics is also consistent with observations from conventional treatment studies (Moreira et al., 2023). Additional settling provided diminishing benefits, while filtration reduced differences between sedimentation times, in line with related treatment studies (Chuiprasert et al., 2026; Razali, Wahab, Sunar, and Shamsudin, 2023). The effect of treatment time is parameter-dependent: improved clarification does not necessarily imply a proportional decrease in dissolved constituents (Salsabila et al., 2024). Coagulation and downstream separation processes can provide complementary particle-removal functions, although this does not establish the mechanisms underlying the present TDS changes (Malkoske, Bérubé, and Andrews, 2020).

Conductivity-derived TDS decreased from 350 mg/L to 119.5 mg/L for PS and 118.5 mg/L for CE after 2 h of sedimentation and filtration, corresponding to calculated reductions of 65.86% and 66.14%. These estimates were numerically below the <300 mg/L benchmark, but comparison remains provisional because the original EC-to-TDS conversion setting could not be verified and no gravimetric validation was performed. Changes in ionic composition and contributions from preparation media and coagulant constituents were not separately quantified. Accordingly, the results do not establish dissolved-solids mass removal or confirm adsorption and co-precipitation mechanisms; gravimetric validation and a dissolved-constituent mass balance are required.

The pH remained within 6.5–8.5, consistent with maintaining acceptable pH during natural-coagulant treatment (Nguyen et al., 2025). For CE, pH decreased from 7.60 to approximately 6.85 after sedimentation and 6.80–6.90 after filtration. Acetic acid used in CE preparation may have contributed to this decrease, but the effects of the preparation medium and groundwater acid–base chemistry were not separately quantified; this remains a possible explanation rather than a confirmed cause.

The findings demonstrate improvement in the evaluated physicochemical parameters, not safety for direct drinking. DOC, COD, UV_{254}, residual organic constituents, and microbiological indicators were not measured. Broader chemical and microbiological assessment and appropriate disinfection are required before drinking-water use can be considered.



(a) (b)

Figure 6. (a) Turbidity and (b) conductivity-derived TDS of groundwater treated in a pilot-scale coagulation, flocculation, sedimentation, and filtration system using papaya seed and chicken eggshell coagulants. Values represent the means of two measurements of the same sample from a single treatment run; independent treatment replicates were not performed.

Table 2. Groundwater quality testing in pilot scale coagulation, flocculation, sedimentation and filtration reactors

Parameter	Unit	Standards*	Initial	SD1		SD1+FT		SD1.5		SD1.5+FT		SD2		SD2+FT	
				PS	CE	PS	CE	PS	CE	PS	CE	PS	CE	PS	CE
pH	-	6.50 – 8.50	7.60	7.60	6.85	7.15	6.80	7.60	6.85	7.20	6.90	7.60	6.85	7.20	6.85
Temperature	℃	Air temp. ± 3.0	26.7	26.7	26.7	26.7	26.7	26.7	26.7	26.7	26.7	26.7	26.7	26.7	26.7
Nitrite	mg/L	3.000	0.014	0.012	0.010	0.005	0.005	0.009	0.010	0.003	0.003	0.007	0.010	0.001	0.000
Nitrate	mg/L	20.000	0.028	0.024	0.020	0.004	0.004	0.022	0.020	0.003	0.002	0.018	0.018	0.000	0.000
Iron (Fe)	mg/L	0.200	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Manganese (Mn)	mg/L	0.100	0.100	0.075	0.070	0.005	0.005	0.040	0.040	0.003	0.002	0.020	0.030	0.000	0.000

** Benchmark values were taken from the Annex to Indonesian Ministry of Health Regulation No. 2 of 2023. Meeting the evaluated physicochemical benchmarks does not demonstrate safety for direct drinking. Values represent the means of two measurements of the same sample from a single treatment run; independent treatment replicates were not performed.*

3.6 Practical Implications of Biocoagulant Dosage, Residual Solids, and Cost

To assess the practical implications of the selected biocoagulant dose, a preliminary material-demand and cost estimate was prepared using the cost assumptions reported in the underlying pilot-scale studies. At the selected dose of 500 mg/L, both papaya seed (PS) and chicken eggshell (CE) biocoagulants require 0.50 g of dry material per litre of groundwater treated. This corresponds to 112.5 g per 225-L pilot batch and approximately 0.338 kg/day at the assumed treatment volume of 675 L/day. The estimated cost and material requirements are summarized in Table 3.

A preliminary cost reconciliation was performed using 225 L of groundwater per pilot batch and an assumed groundwater treatment volume of 675 L/day. Annual costs were calculated assuming 365 operating days per year. These volumes were used as separate calculation bases and do not represent a verified daily operating schedule. The source-reported unit-cost estimates were IDR 254.26/L for PS and IDR 230.70/L for CE. Applying these values consistently gives allocated batch costs of IDR 57,208.50 and IDR 51,907.50, daily costs of IDR 171,625.50 and IDR 155,722.50, and annual costs of IDR 62,643,307.50 and IDR 56,838,712.50 for PS and CE, respectively. These calculations reconcile the displayed unit costs but do not independently validate the underlying component-level estimates. Inconsistencies in the source cost breakdown, particularly for CE, require resolution before drawing conclusions about the relative economic advantage of the two preparations.

Table 3. Material requirements and arithmetic reconciliation of source-reported unit-cost estimates under the assumed treatment schedule

Parameter	Papaya seed (PS) biocoagulant	Chicken eggshell (CE) biocoagulant
Operating assumptions		
Groundwater volume per batch (L/batch)	225	225
Assumed number of batches per day	3	3
Assumed groundwater treatment volume (L/day)	675	675
Assumed operating days per year (days/year)	365	365
Starting-material requirements		
Selected nominal dose (mg/L groundwater)	500	500

Parameter	Papaya seed (PS) biocoagulant	Chicken eggshell (CE) biocoagulant
Dry starting-material equivalent (g/L groundwater)	0.50	0.50
Dry starting-material requirement per batch (g/batch)	112.50	112.50
Dry starting-material requirement per day (kg/day)	0.3375	0.3375
Cost reconciliation—not component-validated		
Source-reported unit-cost estimate (IDR/L groundwater)	254.26	230.70
Calculated allocated cost per batch (IDR/batch)	57,208.50	51,907.50
Calculated daily cost (IDR/day)	171,625.50	155,722.50
Calculated annual cost (IDR/year)	62,643,307.50	56,838,712.50

Note: *Material quantities are dry starting-material equivalents. Unit-cost estimates are from Cahyaningrum (2023, Table 4.14) for PS and Rifqyawarman (2023, Table 4.14) for CE. Costs were recalculated using 225 L/batch, 675 L/day, and 365 days/year, without intermediate rounding. These are calculation assumptions, not verified operation; component costs remain unvalidated.*

4. Conclusions

This exploratory study evaluated papaya seed (PS) and chicken eggshell (CE) preparations through jar-test screening and pilot-scale groundwater treatment. The selected nominal mixing targets were coagulation $G{\cdot}t_d$ of 48,000 and flocculation $G{\cdot}t_d$ of 28,000, with a nominal starting-material dose of 500 mg/L and 150-mesh precursor powder. Under the selected jar-test condition, turbidity removal and conductivity-derived TDS reduction were 96.54% and 44.86% for PS and 94.26% and 44.71% for CE, respectively. Following pilot treatment with 2 h sedimentation and filtration, turbidity removal reached 97.04% and 97.23%, while calculated TDS reductions were 65.86% and 66.14%. Reported manganese concentrations also decreased, whereas pH, nitrite, nitrate, and iron were already within their respective benchmarks in the raw groundwater. These numerical results do not establish superiority of either preparation.

The experiments used one groundwater batch and single treatment runs; duplicate sample measurements were not independent treatment replicates. Accordingly, the selected conditions are preliminary rather than a confirmed optimum. Final conductivity-derived TDS estimates of 119.5 and 118.5 mg/L were numerically below the <300 mg/L benchmark, but the original conversion and calibration settings could not be verified and gravimetric validation was not performed. Precursor composition was interpreted descriptively, and neither the actual dissolved contribution of CE nor the mechanisms underlying TDS changes were quantified. The nominal dose requires 112.5 g of starting material per 225-L batch, equivalent to approximately 0.338 kg/day at an assumed capacity of 675 L/day. Unresolved component-level cost inconsistencies prevent a reliable economic comparison.

The findings indicate preliminary physicochemical improvement, not safety for direct drinking or demonstrated operational sustainability. Microbiological and organic-matter indicators, sludge production, and preparation-energy demand were not evaluated. Further work should include independent treatment replication across groundwater batches, gravimetric and dissolved-ion validation, preparation-medium controls, residual-coagulant and sludge characterization, component-based costing, and energy and life-cycle assessment. Broader chemical and microbiological assessment and appropriate disinfection are required before drinking-water use can be considered.

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Ethics Statement

This research did not involve human participants, human data or tissue, or animal experiments. All experiments were performed on groundwater and agrowaste-derived biocoagulants (papaya seeds and chicken eggshells) under controlled laboratory and pilot-scale conditions. According to the policies of Universitas Trisakti, this type of study does not require approval from an Institutional Review Board or Animal Ethics Committee, and no specific ethics approval was therefore sought.

CRediT Author Statement

Riana Ayu Kusumadewi: Idea Development, Research Design, Program Development, Data Curation, Manuscript Draft Preparation, Manuscript Review and Revision, Visualization, Supervision, Financial Support Acquisition. **Winarni:** Idea Development, Research Design, Result Verification, Resources, Data Curation, Supervision. **Nadia Amalia Cahyaningrum:** Program Development, Formal Analysis, Investigation. **Hanief Rifqyawarman:** Program Development, Formal Analysis, Investigation. **Rositayanti Hadisoebroto:** Result Verification, Resources, Project Administration. **Sheilla Megagupita Putri Marendra:** Program Development, Investigation, Data Curation, Visualization. **Chandra S. Rahendaputri:** Research Design, Result Verification, Resources, Data Curation, Visualization, Project Administration.

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