

Integrated electrocoagulation, anaerobic-aerobic biofiltration and zeolite-activated carbon polishing of batik wastewater for on-site water reuse

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ABSTRACT

Batik wastewater is deeply colored and carries a heavy organic and solids load, because the naphthol and indigosol dyes used in hand-drawn production resist conventional biological treatment. This study tested whether a three-stage train of iron–aluminum electrocoagulation, attached-growth biofiltration and zeolite–granular activated carbon polishing can turn such wastewater into water fit for reuse inside the workshop that produced it. Six electrode–current combinations were screened at 3 A and 5 A for 30 min, aerobic and sequential anaerobic–aerobic biofilters were compared over hydraulic retention times of 15–50 h, and the polishing column was run in continuous downflow at an empty-bed contact time of 4.59 h. Every condition was repeated in three independent runs. The raw wastewater contained 3918.4 mg/L chemical oxygen demand (COD), 1533.0 mg/L five-day biochemical oxygen demand (BOD₅), 1080 mg/L total suspended solids (TSS), 3715 mg/L total dissolved solids (TDS), 967 Pt-Co of color and 184 mg/L of oil and grease. Alternating iron and aluminum plates at 5 A gave the most balanced pretreatment, removing 56.1% of COD, 60.0% of BOD₅, 76.9% of TSS, 88.2% of total phosphorus and 84.0% of color, although TDS rose by 44.2% as the sacrificial plates dissolved. At a total retention time of 50 h the sequential biofilter outperformed the aerobic-only reactor for every parameter, lowering COD to 152.6 mg/L against 593.5 mg/L. The layered zeolite–activated carbon bed then delivered 3.7 mg/L COD, 0.10 mg/L BOD₅, 1.0 mg/L TSS, 155 mg/L TDS and 1 Pt-Co of color, with phosphorus, nitrogen species and oil and grease below their reporting limits. The final water satisfied every physicochemical criterion of the Indonesian river water quality standard and is fit for return to the non-potable stages of batik production, which points to a workable closed water loop for small producers.

Keywords: batik wastewater; electrocoagulation; anaerobic–aerobic biofiltration; activated carbon; zeolite; water reuse.

INTRODUCTION

Batik production carries cultural and economic weight in Indonesia, yet its wet processing releases a wastewater whose composition shifts from one workshop to the next and even from one batch to the next, carrying dyes, wax residues, salts, surfactants, nutrients, suspended matter and occasionally trace metals (Yaseen &

Scholz, 2019; Zakaria et al., 2023). Color limits light penetration in receiving waters, while the oxygen demand and the persistent aromatic fraction place further pressure on aquatic ecosystems (Abiri et al., 2017; Almadani, 2023). Small and medium-sized producers face the sharpest version of this problem: their effluent varies with production practice, and any treatment unit has to run compactly and with little technical supervision

(Pramugani et al., 2020; Purwaningrum et al., 2023). Recent work has therefore moved towards treatment trains that pair load reduction with biological and polishing stages rather than relying on a single unit (Ardhianto et al., 2025; Vistanty et al., 2025). Figure 1 shows the dye-dissolving step of hand-drawn batik production, the point at which most of the color load enters the wastewater.

Electrocoagulation is an attractive first stage because sacrificial iron or aluminum electrodes generate coagulant species in situ. Charge neutralization, adsorption onto metal hydroxides, sweep flocculation and electroflotation together remove colloids and chromophores within minutes (Garcia-Segura et al., 2017; Hakizimana et al., 2017). The drawbacks are equally well documented: electrode passivation, sludge production, the accumulation of dissolved ions, and incomplete oxidation of dissolved organic matter (Mao et al., 2023; Moussa et al., 2017). Applied to batik effluent, electrocoagulation removes color and organic load efficiently (Fadzli et al., 2024; Mukimin et al., 2018), but it rarely reaches a quality that permits reuse, so a downstream process is needed whenever the objective extends beyond decolorization (Ardhianto et al., 2025; Bilińska et al., 2019).

Sequential anaerobic–aerobic treatment supplies two complementary reaction environments for dye-bearing wastewater (Abiri et al., 2017; Yurtsever et al., 2016). Under oxygen-limited conditions, hydrolysis and reductive reactions break complex color-bearing molecules into smaller intermediates; the aerobic stage that

follows oxidizes those intermediates and the reduced nitrogen species. Attached-growth systems add a further advantage, since biofilm retains slow-growing organisms and absorbs swings in hydraulic and organic loading (Holkar et al., 2016; Katheresan et al., 2018). Studies on real textile wastewater consistently report better overall performance from the two environments in series than from either alone (Ayed et al., 2021; Kozak et al., 2021), and the same pattern holds in integrated biological reactors (Saleem et al., 2022; Shoukat et al., 2019).

Reaching clean-water quality demands a final purification stage, in this case measured against Government Regulation of the Republic of Indonesia No. 22 of 2021, which sets the class I river water quality standard. Granular activated carbon offers a large surface area with affinity for residual organic molecules, while natural zeolite contributes ion-exchange sites for ammonium and selected cations (Alawam et al., 2025; Almadani, 2023). Placing these media after biological load reduction limits competition for adsorption sites and avoids exhausting the adsorbent on a load that cheaper processes could have removed (Titah & Nasir, 2024; Vecino & Reig, 2022). Adsorption behavior nevertheless remains sensitive to the composition and salinity of the matrix (Sodha et al., 2022; Wang et al., 2022).

What separates the present work from earlier integrated studies is its endpoint. The train was not operated until the effluent met discharge limits, but until the water could be returned to the batik process itself. Three questions follow from that aim: how the pollutant load responds to the



Figure 1. The batik-making process: (a) dissolving the primary dye, (b) batik wastewater after dyeing process (photographs taken by N. Hendrasarie, Jetis, Sidoarjo, July 2026)

iron–aluminum electrode arrangement and to the applied current; whether a sequential anaerobic–aerobic fixed bed outperforms an aerobic fixed bed as retention time is extended; and what final quality a layered zeolite–activated carbon bed can deliver from real, high-strength batik wastewater. The answers also indicate how much of a workshop’s freshwater demand such a system might displace.

MATERIALS AND METHODS

Wastewater source and characterization

Composite wastewater was collected from a small-scale batik production cluster in Jetis, Sidoarjo, East Java, Indonesia. The sample combined the effluent of the wet processing activities and was homogenized before characterization and treatment. Initial analyses covered pH, dissolved oxygen, color, chemical oxygen demand, five-day biochemical oxygen demand, total suspended solids, total dissolved solids, total phosphorus, ammonia nitrogen, total Kjeldahl nitrogen, calcium, and oil and grease.

Experimental treatment train

The laboratory train comprised electrocoagulation, primary clarification, attached-growth bio-filtration, secondary clarification and continuous downflow adsorption. Each nominal hydraulic retention time (HRT) was run in a separate bio-filter operated at the corresponding flow rate, and the aerobic-only and sequential anaerobic–aerobic configurations were compared at matched nominal HRTs. Table 1 summarizes the operating specifications of each unit.

Electrocoagulation

The electrocoagulation reactor was operated at a nominal 12 V in a monopolar arrangement. Three plate sequences were evaluated: Fe–Fe–Fe–Fe–Fe–Fe, Fe–Al–Al–Fe–Al–Al and alternating Fe–Al–Fe–Al–Fe–Al. Each sequence was tested at 3 A and 5 A for 30 min, followed by 30 min of quiescent settling. The active submerged plate area was 0.156 m², giving a current density of 32.05 A/m² at 5 A. Conductivity of the wastewater before treatment was 5.8 mS/cm and temperature was held at

30 ± 2 °C. Plates were mechanically polished, rinsed in 0.1 M hydrochloric acid and washed with water before each run. The operating condition was selected from the combined response of organic matter, suspended solids, nutrients, color, and oil and grease rather than from any single parameter. On a nominal power basis, the selected 12 V, 5 A, 30 min condition corresponds to about 3.0 kWh/m³ of treated wastewater, excluding power-supply losses.

Biofilter start-up and hydraulic retention time

Both biological configurations were packed with polypropylene bio balls at a 40% packing fraction; the media have a specific surface area of 220 m²/m³ and a void ratio above 90%. Indigenous biofilm was acclimatized for four weeks before the comparison began. Separate 10 L reactors were assigned to nominal HRTs of 15, 20, 25, 40 and 50 h for each configuration. From $Q = V/\text{HRT}$, the corresponding influent flow rates were 0.667, 0.500, 0.400, 0.250 and 0.200 L/h. Every reactor ran in continuous once-through mode without recirculation, and effluent was collected after one nominal HRT, equivalent to a single hydraulic volume replacement. Each HRT condition was repeated in three independent runs. The data therefore describe a comparative short-duration HRT screening and are not presented as steady-state continuous-reactor performance. In the sequential reactor the total retention time was split equally between the anaerobic and aerobic zones. Dissolved oxygen was held below 0.5 mg/L in the anaerobic zone and between 6.6 and 7.8 mg/L in the aerobic zone, at 29 ± 2 °C. At the selected 50 h condition the organic loading rate was 0.825 kg COD/(m³·d). Without any chemical addition, the pH fell from the alkaline electrocoagulation effluent to 7.0–7.9 during biological treatment.

Dual-media polishing

Effluent from the selected anaerobic–aerobic condition was passed downwards through zeolite, granular activated carbon, or a layered zeolite–activated carbon bed. The rectangular column measured 6 × 6 × 30 cm internally. Media filled 85% of the column height, giving a packed-bed depth of 25.5 cm and a nominal empty-bed volume of 0.918 L. The combined

Table 1. Main treatment-unit specifications

Unit	Working volume or geometry	Media or components	Operating condition
Electrocoagulation	10 L; acrylic tank, 20 × 20 × 30 cm	Six Fe/Al plates, 15 × 10 × 0.1 cm; 1 cm spacing	12 V; 3 or 5 A; 30 min reaction; 30 min settling
Aerobic biofilter	10 L; 20 × 20 × 30 cm	Polypropylene bio balls; 40% v/v; bottom diffuser	Nominal HRT 15, 20, 25, 40, and 50 h; continuous aeration
Anaerobic–aerobic biofilter	10 L total; 5 L anaerobic and 5 L aerobic	Polypropylene bio balls; 40% v/v in both zones	Same total HRT series; equal HRT allocation between zones
Adsorption column	Rectangular column, 6 × 6 × 30 cm; media depth 25.5 cm; empty-bed volume 0.918 L	Layered GAC and natural zeolite at 1:1 volume ratio; 85% bed-height filling	Continuous downflow at 0.2 L/h; EBCT 4.59 h; sampling after ≥1 EBCT

Note: EBCT – empty-bed contact time; GAC – granular activated carbon; HRT – hydraulic retention time.

bed used equal media volumes, about 12.75 cm of each layer, corresponding to roughly 72 g of activated carbon and 135 g of natural zeolite. Both media were washed until the rinse ran clear and then soaked in water. The activated carbon had a particle size of 0.84–2.38 mm and a Brunauer–Emmett–Teller surface area of 950 m²/g; the zeolite had a surface area of 50 m²/g and a cation-exchange capacity of 1.4 meq/g. At 0.200 L/h the nominal empty-bed contact time (EBCT) was 4.59 h. The column was operated for at least one EBCT before time-profile sampling, so that the initial liquid was displaced and downflow conditions were established, after which samples were taken over 0–150 min. These are elapsed post-EBCT sampling times and not different contact times. Since the test covers short-term polishing rather than exhaustion of the bed, the results are not interpreted as a complete breakthrough assessment.

Analytical methods and data treatment

Water-quality parameters were measured by APHA Standard Methods and, where applicable, the corresponding Indonesian National Standards. Chemical oxygen demand was determined by closed-reflux colorimetry, five-day biochemical oxygen demand by incubation at 20 °C, solids by gravimetry, color by the platinum–cobalt method and calcium by atomic absorption spectrometry; nutrients and oil and grease were measured by the relevant spectrophotometric and gravimetric partition methods, and pH and dissolved oxygen with a calibrated multiparameter meter (Table 2). Laboratory blanks, matrix spikes and duplicate measurements served as quality-control checks: matrix-spike recovery ranged from 95% to 104% and the relative percentage difference between duplicates stayed below 5%. All treatment

conditions were evaluated in three independent runs ($n = 3$), and concentrations are reported as mean $\pm$ sample standard deviation across those runs. Removal efficiency was calculated for each run against its own initial measurement and then summarized in the same way. Comparisons are descriptive rather than inferential; with three observations per condition, null-hypothesis tests offer little diagnostic value, and the experiment was designed as engineering screening. Values reported as zero by an instrument are interpreted against the verified laboratory reporting limit and not as absolute absence.

Assessment of reuse potential

Fitness of the final effluent for on-site reuse was judged against the parameters that govern water use in the batik process. Samples were drawn from the outlet of the zeolite–granular activated carbon column once the bed had been operated for at least one empty-bed contact time. Three samples from three independent runs were analyzed for chemical oxygen demand, five-day biochemical oxygen demand, total suspended solids, total dissolved solids, color, total Kjeldahl nitrogen, ammonia nitrogen, calcium, oil and grease, dissolved oxygen and pH, following the 24th edition (2023) of Standard Methods for the Examination of Water and Wastewater of the American Public Health Association.

Recycling potential was then estimated by comparing the volume of treated water that met these criteria with the water demand reported by the workshop during interviews. No recycling loop was installed at production scale, so the freshwater replacement quoted below is a projection from the laboratory water balance rather than an observed reduction in industrial consumption.

Table 2. Analytical methods and reported detection limits

Parameter	Method	Detection limit
Chemical oxygen demand	APHA 5220 D; closed-reflux colorimetry	1.5 mg/L
Five-day biochemical oxygen demand	APHA 5210 B; 5 d at 20 °C	0.1 mg/L
Total suspended solids	APHA 2540 D; gravimetry	0.5 mg/L
Total dissolved solids	APHA 2540 C; gravimetry	1.0 mg/L
Total phosphorus	APHA 4500-P	0.01 mg/L
Color	APHA 2120 C; platinum–cobalt scale	1 Pt-Co
Total Kjeldahl nitrogen; NH ₃ –N	APHA 4500 N series	0.01 mg/L
Oil and grease	APHA 5520 B	0.01 mg/L
Calcium	APHA 3500-Ca B	1.0 mg/L

RESULTS AND DISCUSSION

Electrocoagulation pretreatment

Of the six current–electrode combinations, alternating Fe–Al–Fe–Al–Fe–Al plates at 5 A gave the most balanced response across the parameters evaluated. Table 3 lists the initial concentration, the effluent under that condition and the resulting change. Chemical oxygen demand and five-day biochemical oxygen demand fell by 56.1% and 60.0%; total suspended solids by 76.9%, total phosphorus by 88.2%, ammonia nitrogen by 26.2%, total Kjeldahl nitrogen by 66.5%, color by 84.0%, oil and grease by 67.4% and calcium by 46.6%.

For all three plate arrangements the removal efficiency obtained at 5 A exceeded that at 3 A for every parameter measured (Figures 2, 3 and 4). The difference follows from Faraday’s law. A higher current accelerates anodic dissolution, so

more iron and aluminum ions enter the solution per unit time and more hydroxide nuclei become available to destabilize colloids and bind dissolved organic matter; at 3 A the supply of coagulant is smaller and part of the pollutant load remains unbound when the 30 min reaction period ends. Cathodic hydrogen evolution scales in the same way, and the denser, finer bubble curtain generated at 5 A carries flocs to the surface more effectively, where they accumulate as scum and are separated from the treated water. The higher cell current also raises the potential available for direct oxidation at the anode surface, which contributes to the breakdown of the complex organic molecules that reach it. These three mechanisms together account for the choice of the 5 A condition and match the current dependence reported for integrated electrocoagulation of textile and batik effluent (Ardhianto et al., 2025; Mukimin et al., 2018).

Table 3. Performance of the selected electrocoagulation condition

Parameter	Initial, mean ± SD	After electrocoagulation, mean ± SD	Change (%)
COD (mg/L)	3918.4 ± 80.1	1720.0 ± 35.0	56.1 removal
BOD ₅ (mg/L)	1533.0 ± 35.5	613.2 ± 12.6	60.0 removal
TSS (mg/L)	1080 ± 20	250 ± 5	76.9 removal
TDS (mg/L)	3715 ± 100	5357.8 ± 120.0	44.2 increase
Total phosphorus (mg/L)	3.47 ± 0.08	0.41 ± 0.01	88.2 removal
NH ₃ –N (mg/L)	4.20 ± 0.10	3.10 ± 0.05	26.2 removal
Total Kjeldahl nitrogen (mg/L)	109.3 ± 2.2	36.6 ± 0.8	66.5 removal
Color (Pt-Co)	967 ± 17	155 ± 3	84.0 removal
Oil and grease (mg/L)	184 ± 4	60 ± 1	67.4 removal
Calcium (mg/L)	569 ± 6	303.6 ± 9.4	46.6 removal
pH	7.5 ± 0.1	9.2 ± 0.1	Increase
Dissolved oxygen (mg/L)	2.0 ± 0.1	3.0 ± 0.1	Increase

Note: n = 3. Selected condition: alternating Fe–Al plates, 5 A, 12 V, 30 min reaction and 30 min settling.

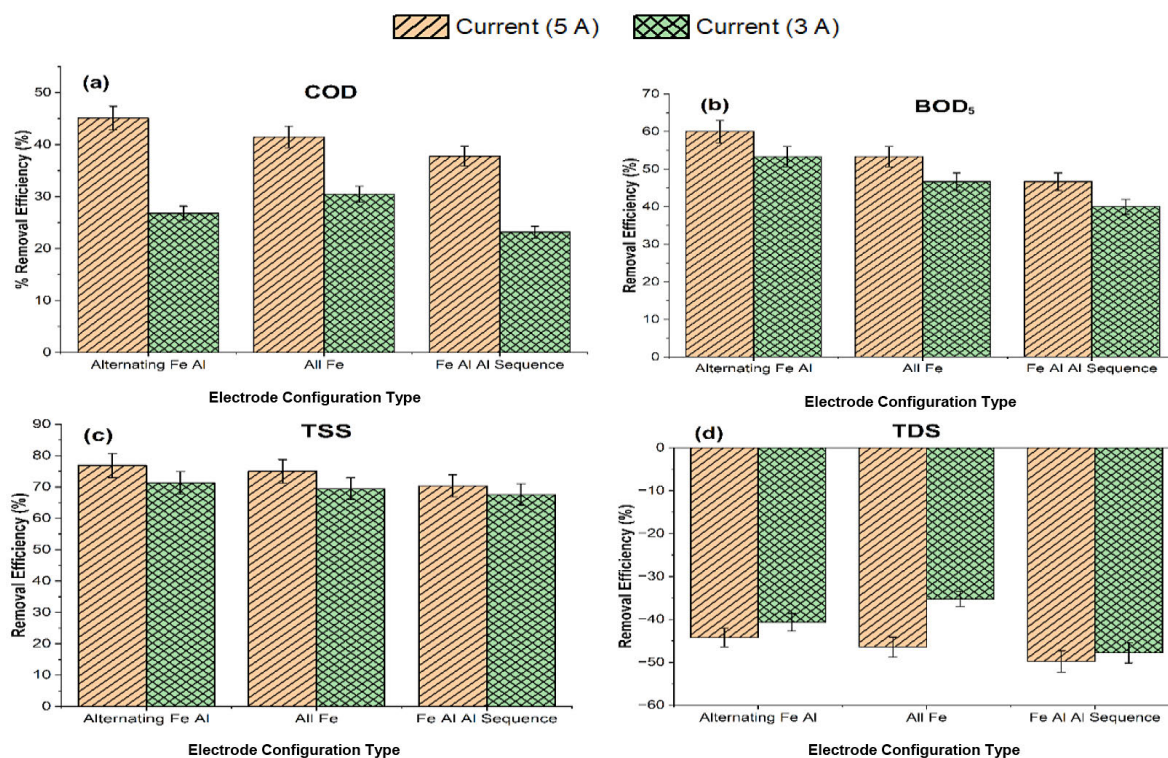


Figure 2. Electrocoagulation removal efficiencies for COD (a), BOD₅ (b), TSS (c) and TDS (d) under three electrode arrangements at 3 A and 5 A. Bars and error bars represent mean ± SD (n = 3)

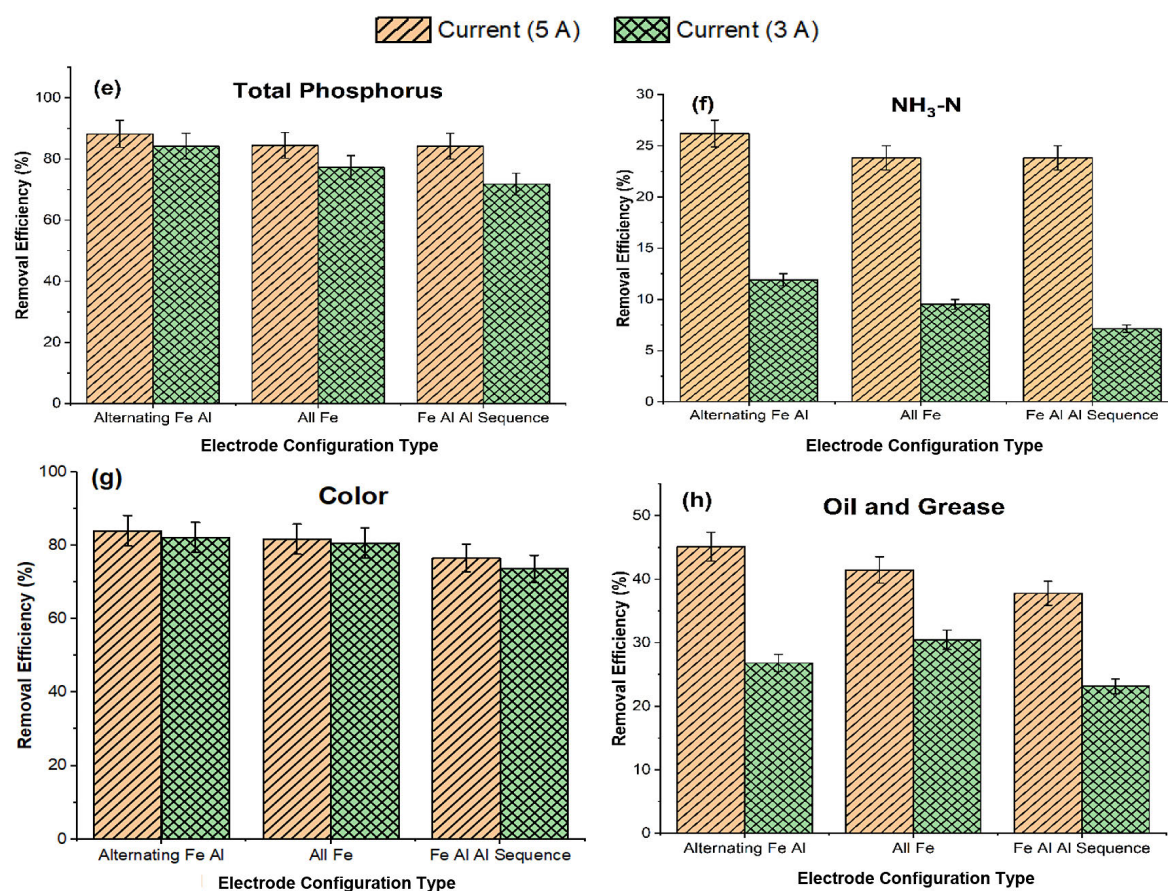


Figure 3. Electrocoagulation removal efficiencies for total phosphorus (e), ammonia nitrogen (f), color (g) and oil and grease (h) under three electrode arrangements at 3 A and 5 A. Bars and error bars represent mean ± SD (n = 3)

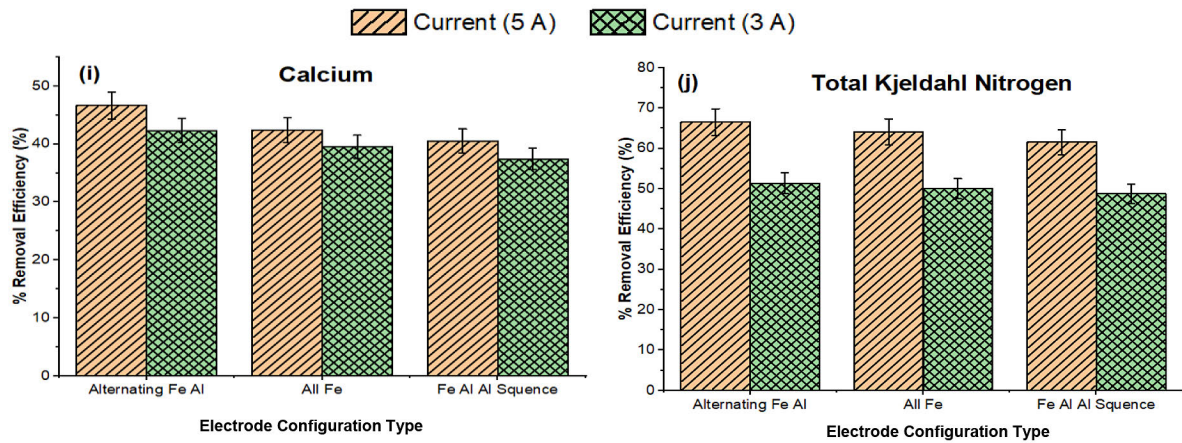


Figure 4. Electrocoagulation removal efficiencies for calcium (i) and total Kjeldahl nitrogen (j) under three electrode arrangements at 3 A and 5 A. Bars and error bars represent mean $\pm$ SD (n = 3)

The alternating sequence combines iron and aluminum hydroxide species, which destabilize colloids and adsorb color-bearing compounds. Removing 84.0% of the color within 30 min agrees with recent reports on batik effluent, although the reported figures vary with current, electrolyte concentration, contact time and wastewater composition (Fadzli et al., 2024; Zakaria et al., 2023). Electrode configuration and operating conditions also govern hydroxide generation, energy demand and solids production (Garcia-Segura et al., 2017; Moussa et al., 2017).

Total dissolved solids rose in every electrode configuration. Dissolution of the sacrificial plates, together with ionic constituents that survive the process, shifts part of the pollutant load from the suspended and colloidal fraction into the dissolved one, and cathodic hydroxide generation accounts for the alkaline effluent. This is the clearest argument for

treating electrocoagulation as a load-reduction step rather than a stand-alone route to high-quality water (Garcia-Segura et al., 2017; Mao et al., 2023).

Comparison of biofilter configurations

Table 4 compares the two biofilter configurations at the selected 50 h hydraulic retention time. Percentages are cumulative removals relative to the raw wastewater, not removals within the biological reactor alone. The sequential anaerobic–aerobic reactor produced lower final concentrations than the aerobic-only system for every parameter measured, and the gap was widest for chemical oxygen demand: 152.6 mg/L against 593.5 mg/L.

The advantage of the sequential system over the aerobic-only reactor (Figures 5, 6 and 7) rests on two complementary microbial environments acting on an organic fraction that is far

Table 4. Biofilter performance at 50 h total hydraulic retention time

Parameter	Aerobic-only effluent, mean $\pm$ SD	Aerobic cumulative removal (%)	Anaerobic–aerobic effluent, mean $\pm$ SD	Anaerobic–aerobic cumulative removal (%)
COD (mg/L)	593.5 $\pm$ 7.8	84.9	152.6 $\pm$ 3.1	96.1
BOD ₅ (mg/L)	118.5 $\pm$ 2.2	92.3	68.8 $\pm$ 0.8	95.5
TSS (mg/L)	21.0 $\pm$ 1.0	98.1	18.0 $\pm$ 1.0	98.3
TDS (mg/L)	2049.3 $\pm$ 42.7	44.8	854 $\pm$ 12	77.0
Total phosphorus (mg/L)	0.120 $\pm$ 0.010	96.5	0.047 $\pm$ 0.006	98.7
NH ₃ –N (mg/L)	0.50 $\pm$ 0.01	88.1	0.40 $\pm$ 0.01	90.5
Total Kjeldahl nitrogen (mg/L)	5.60 $\pm$ 0.10	94.9	3.87 $\pm$ 0.06	96.5
Color (Pt–Co)	90 $\pm$ 1	90.7	85 $\pm$ 1	91.2
Oil and grease (mg/L)	5.0 $\pm$ 0.2	97.3	2.0 $\pm$ 0.1	98.9
Calcium (mg/L)	220.7 $\pm$ 4.4	61.2	215.8 $\pm$ 5.6	62.1

Note: n = 3. Cumulative removal was calculated relative to the raw-wastewater mean.

from uniform. In the anaerobic zone, hydrolytic and fermentative organisms cleave the long-chain constituents of batik effluent, chiefly starch, sizing agents and wax residues, into short-chain acids and other simple intermediates; the aerobic zone then mineralizes those intermediates quickly, which explains the low residual chemical oxygen demand and five-day biochemical oxygen demand at 50 h. Suspended solids follow a different route, since the bio balls serve at once as a growth surface and as a depth filter and retain the fine wax particles and fabric fibers that would otherwise pass through. Total dissolved solids declined more modestly, which is attributed to biosorption of salts and mineral ions by the biofilm together with precipitation of calcium carbonate once bacterial activity raises the carbonate concentration; the parallel fall in dissolved calcium supports that reading. Nitrogen was removed mainly through assimilation and through nitrification in the aerobic zone, where ammonia and organic nitrogen are oxidized to nitrite and then nitrate. Because the reactors were operated once-through and without recirculation, denitrification was confined to the nitrate reaching anoxic microsites inside the biofilm

and cannot account for a large share of the nitrogen loss. Oils and fats, hydrophobic and poorly degradable in a single environment, are hydrolyzed to fatty acids and glycerol by extracellular lipases under anaerobic conditions and oxidized in the aerobic stage. Comparable staged behavior has been reported for fixed-film reactors treating other high-strength industrial effluents (Hendrasarie & Zarfandi, 2023; Hendrasarie et al., 2024).

Taking the electrocoagulation effluent as the biological influent, the sequential reactor removed a further 91.1% of the residual chemical oxygen demand and 88.8% of the residual five-day biochemical oxygen demand; comparable gains have been reported for sequential redox treatment of real colored and textile wastewater (Ayed et al., 2021; Shoukat et al., 2019). Dissolved oxygen stayed below 0.5 mg/L in the anaerobic compartment and above 6.6 mg/L in the aerobic compartment, so the two environments remained operationally distinct, and the near-neutral effluent pH indicates that the biological reactions consumed the alkalinity generated during electrocoagulation. Attached biomass and the four-week acclimatization period also limited the risk of washout as flow rates increased.

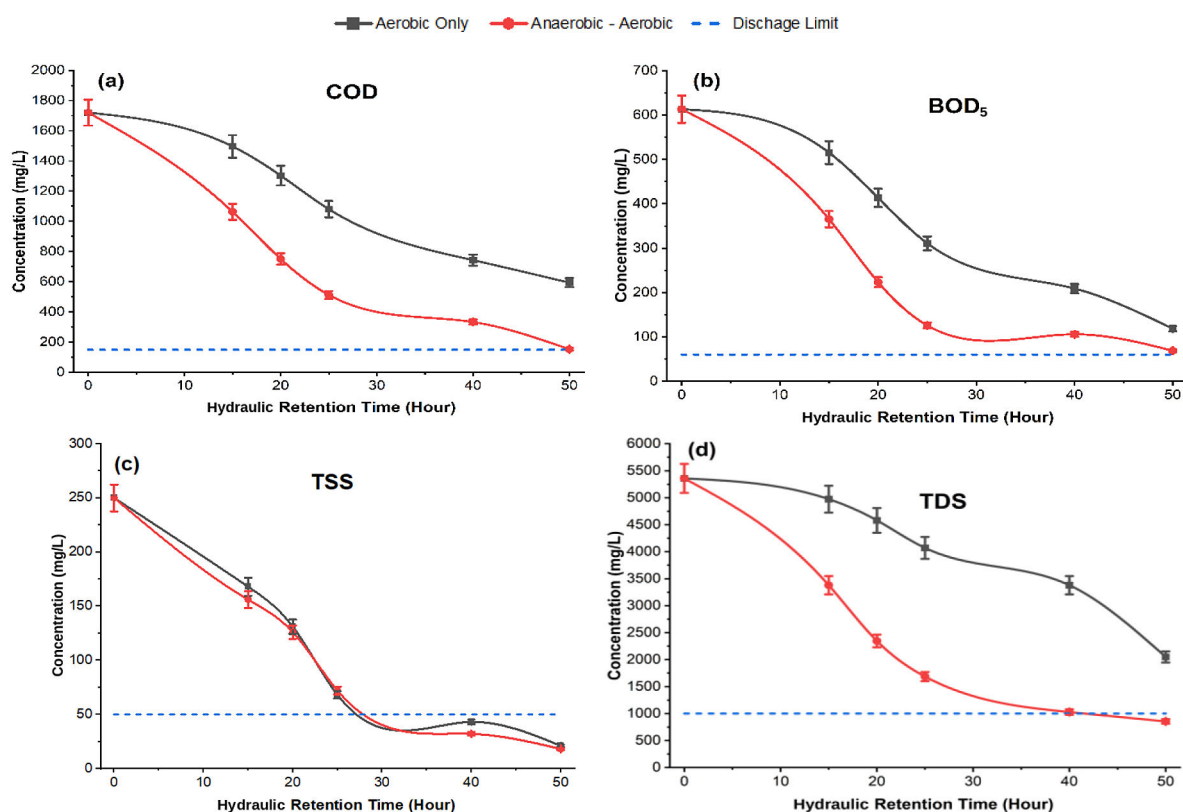


Figure 5. Concentration profiles for COD (a), BOD₅ (b), TSS (c) and TDS (d) in aerobic-only and sequential anaerobic-aerobic biofilters. Points and error bars represent mean $\pm$ SD ($n = 3$); dashed lines show the wastewater-discharge limits recorded in the dataset

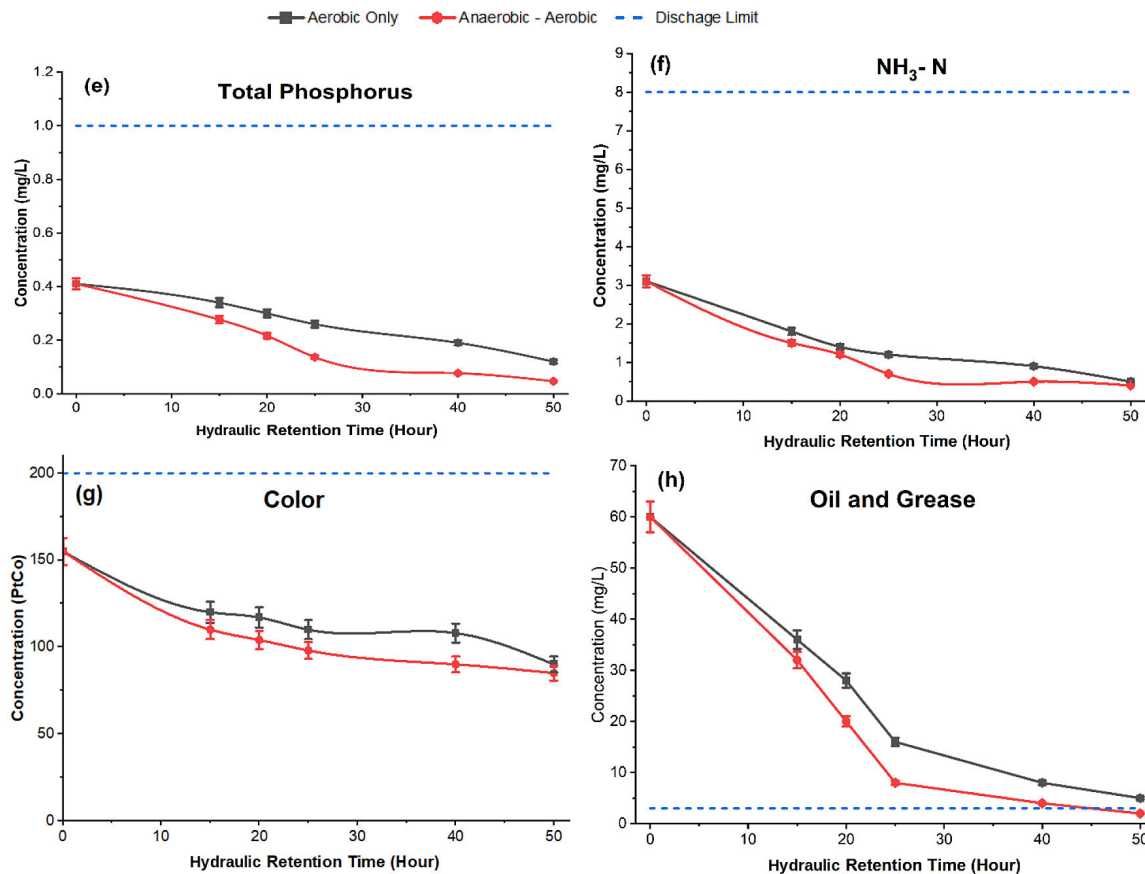


Figure 6. Concentration profiles for total phosphorus (e), ammonia nitrogen (f), color (g) and oil and grease (h) in aerobic-only and sequential anaerobic–aerobic biofilters. Points and error bars represent mean $\pm$ SD ($n = 3$); dashed lines show the wastewater-discharge limits recorded in the dataset

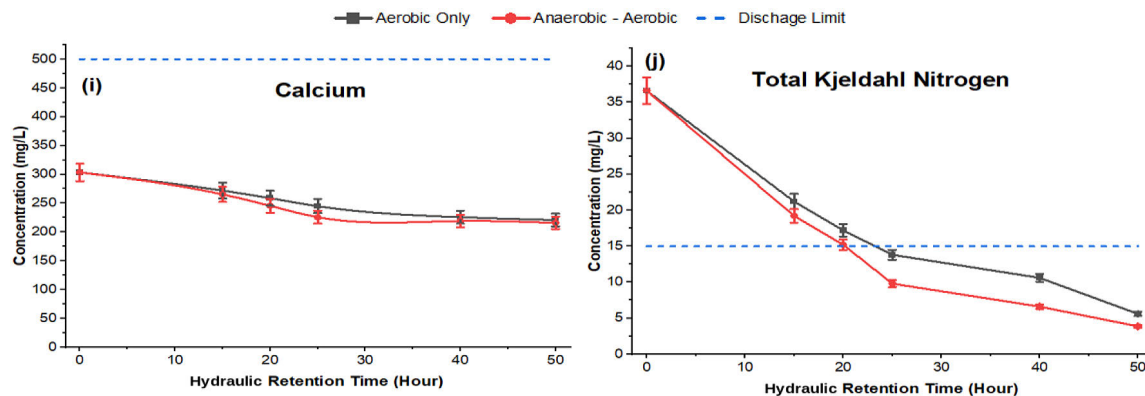


Figure 7. Concentration profiles for calcium (i) and total Kjeldahl nitrogen (j) in aerobic-only and sequential anaerobic–aerobic biofilters. Points and error bars represent mean $\pm$ SD ($n = 3$); dashed lines show the wastewater-discharge limits recorded in the dataset

Zeolite–activated carbon polishing

The combined zeolite–activated carbon bed reached the lowest minimum concentrations for chemical oxygen demand and five-day biochemical oxygen demand and matched the lowest values observed for total suspended solids and color

(Table 5). The full profiles show a rebound after the minimum, in the case of granular activated carbon after 40 min and in the combined bed after 90 min. Because time-profile sampling began only after the column had run for at least one EBCT, the times quoted are elapsed post-EBCT sampling times rather than contact times; 90 min is thus the

time of the lowest observed mean for the combined bed within the sampling window, not an optimum EBCT or evidence of steady-state operation.

The combined bed outperformed either single medium (Figures 8, 9 and 10) because the two materials cover different regions of the pollutant size and polarity spectrum. Granular activated carbon is dominated by meso- and macropores and by a hydrophobic surface, which suits the large azo dye molecules and the residual wax hydrocarbons that carry most of the color, and it binds them mainly through dispersion forces. Zeolite is microporous and polar, with a high cation-exchange capacity, so it retains small organic molecules, cationic dyes and dissolved cations such as calcium. Layering the two spans the pore range from macro to micro: the coarser fraction is captured in the carbon layer, the residual dissolved fraction in the zeolite, and polar and non-polar species are removed within a single flow path. One practical consequence is that carbon pores are not blocked immediately by the coarse fraction, nor is the outer surface of the zeolite sealed by large dye molecules before micropollutants can reach its micropores. How far this delays saturation cannot be quantified from the present short-duration test.

Placing the adsorption step after biological load reduction limits competition for the available sites and improves use of the adsorbent (Qisti et al., 2021; Titah & Nasir, 2024). A final pH of 6.6–7.0 and dissolved oxygen of 6.3–6.8 mg/L show that polishing left the near-neutral biological effluent undisturbed.

This short post-EBCT test demonstrates a clear improvement in final water quality but says

nothing about bed capacity, service life or exhaustion behavior, so no breakthrough model or regeneration cycle is proposed here. Longer-term adsorption performance depends on bed depth, flow distribution, competing ions, influent variability and cumulative mass loading (Selvaraj & Arivazhagan, 2024; Vecino & Reig, 2022).

Integrated treatment performance

The train reduced a heavy initial load in stages rather than through any single unit. Electrocoagulation brought chemical oxygen demand down from 3918.4 ± 80.1 to 1720.0 ± 35.0 mg/L and color from 967 ± 17 to 155 ± 3 Pt-Co. Anaerobic–aerobic biofiltration then lowered chemical oxygen demand to 152.6 ± 3.1 mg/L and color to 85 ± 1 Pt-Co, and after 90 min of post-EBCT sampling the combined polishing bed delivered 3.7 ± 0.1 mg/L and 1.0 ± 0.1 Pt-Co (Table 6).

These physicochemical results satisfy the listed river water quality standards, but they do not establish potable safety: microbiological indicators and other use-specific parameters were outside the scope of this work. The defensible conclusion is that the integrated system produced a high-quality effluent with reuse potential for applications whose suitability would be confirmed by fit-for-purpose testing, not that it produced drinking water.

Seen as a process, electrocoagulation shielded the biological stage from most of the suspended and color-bearing load, and biofiltration in turn reduced the organic load reaching the adsorbents. The nominal electrocoagulation energy requirement of 3.0 kWh/m³ is the one substantial input,

Table 5. Minimum observed concentrations during the 150 min polishing test

Parameter	Zeolite, mean $\pm$ SD (post-EBCT sampling time)	GAC, mean $\pm$ SD (post-EBCT sampling time)	Zeolite+GAC, mean $\pm$ SD (post-EBCT sampling time)
COD (mg/L)	75.3 ± 1.6 (60 min)	5.9 ± 0.1 (40 min)	3.7 ± 0.1 (90 min)
BOD ₅ (mg/L)	29.2 ± 0.6 (60 min)	2.0 ± 0.1 (40 min)	0.10 ± 0.00 (90 min)
TSS (mg/L)	3.0 ± 0.0 (60 min)	1.0 ± 0.0 (40 min)	1.0 ± 0.0 (90 min)
TDS (mg/L)	210 ± 5 (60 min)	286 ± 6 (40 min)	155 ± 3 (90 min)
Total phosphorus (mg/L)	0.01 ± 0.0 (60 min)	< 0.01 (40 min)	< 0.01 (90 min)
NH ₃ -N (mg/L)	$< \text{LOD}$ (60 min)	0.21 ± 0.1 (40 min)	< 0.01 (90 min)
Total Kjeldahl nitrogen (mg/L)	0.01 ± 0.0 (60 min)	1.5 ± 0.1 (40 min)	< 0.01 (90 min)
Color (Pt-Co)	36.0 ± 0.8 (60 min)	1.0 ± 0.1 (40 min)	1.0 ± 0.1 (90 min)
Oil and grease (mg/L)	0.5 ± 0.0 (60 min)	0.1 ± 0.0 (40 min)	< 0.01 (90 min)
Calcium (mg/L)	43.5 ± 4.9 (60 min)	151.5 ± 5.7 (40 min)	33.2 ± 4.4 (90 min)

Note: n = 3 independent experimental runs. Times indicate the minimum observed mean during post-EBCT sampling; GAC – granular activated carbon.

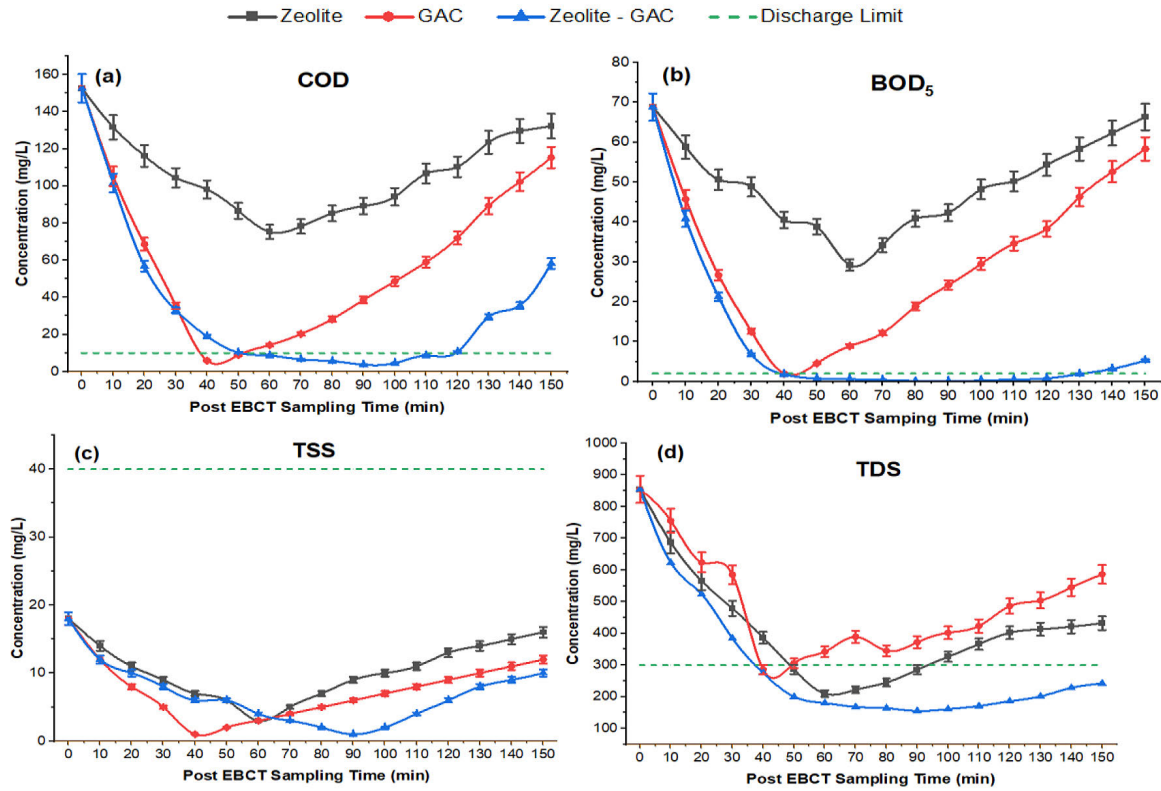


Figure 8. Polishing-stage concentration profiles for COD (a), BOD₅ (b), TSS (c) and TDS (d) with zeolite, granular activated carbon (GAC) and the combined zeolite–GAC bed. Points and error bars represent mean $\pm$ SD ($n = 3$); dashed lines show the discharge limits recorded in the dataset; elapsed time is post-EBCT sampling time and not contact time

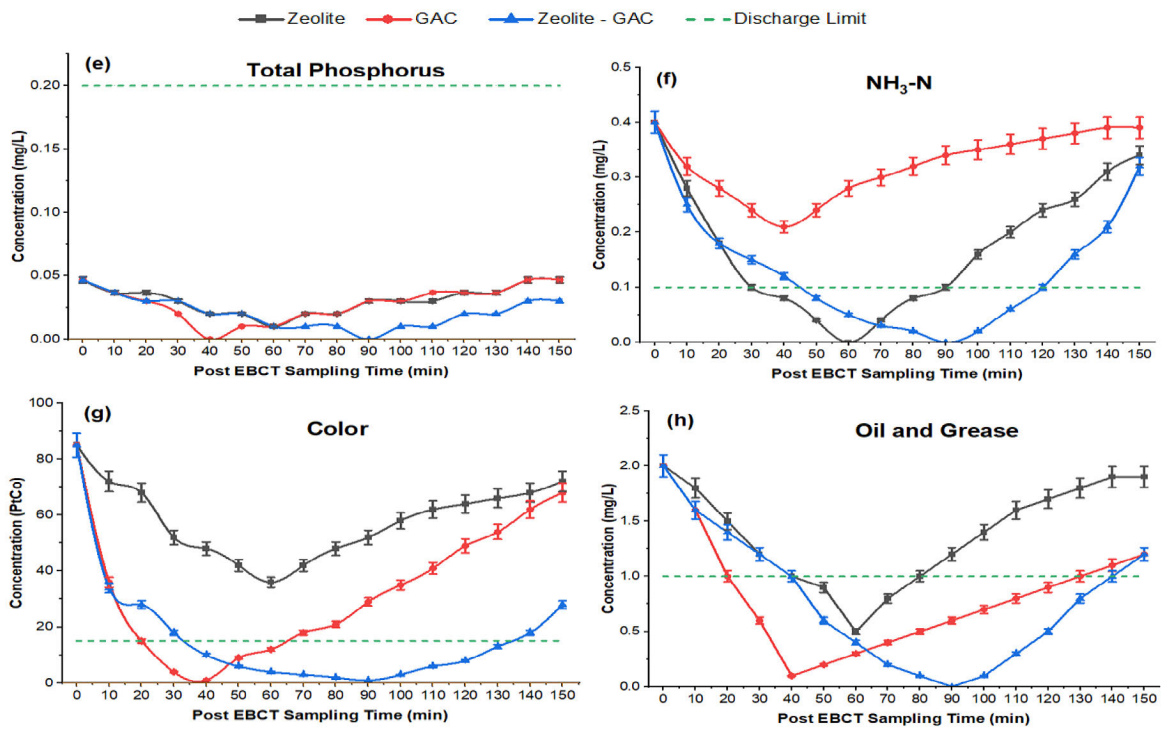


Figure 9. Polishing-stage concentration profiles for total phosphorus (e), ammonia nitrogen (f), color (g) and oil and grease (h) with zeolite, granular activated carbon (GAC) and the combined zeolite–GAC bed. Points and error bars represent mean $\pm$ SD ($n = 3$); dashed lines show the discharge limits recorded in the dataset; elapsed time is post-EBCT sampling time and not contact time

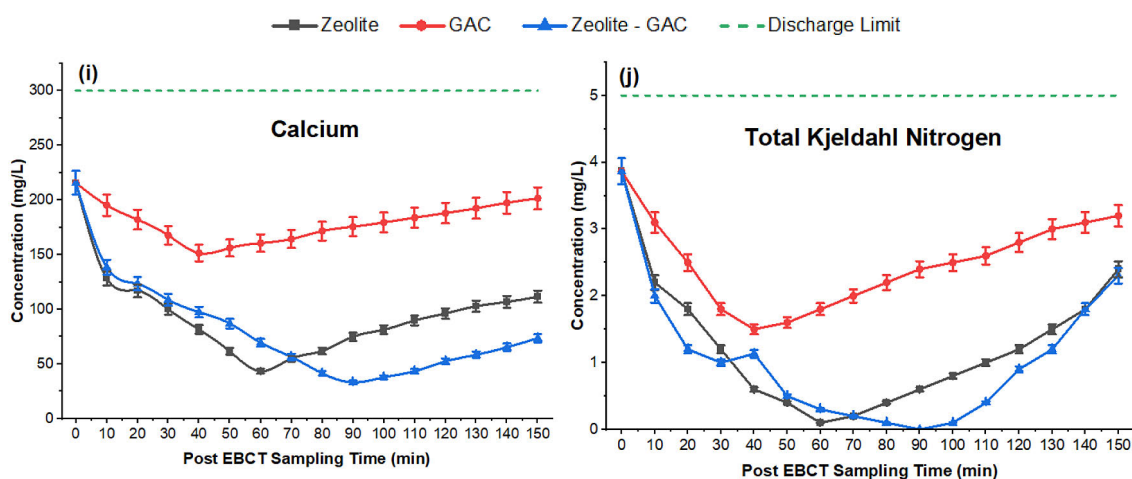


Figure 10. Polishing-stage concentration profiles for calcium (i) and total Kjeldahl nitrogen (j) with zeolite, granular activated carbon (GAC) and the combined zeolite–GAC bed. Points and error bars represent mean $\pm$ SD ($n = 3$); dashed lines show the discharge limits recorded in the dataset; elapsed time is post-EBCT sampling time and not contact time

Table 6. Overall performance and comparison with river water quality standards

Parameter	Raw wastewater, mean $\pm$ SD	Final effluent, mean $\pm$ SD	Overall removal (%)	Standard
COD (mg/L)	3918.4 $\pm$ 80.1	3.7 $\pm$ 0.1 (90 min)	99.91	10
BOD ₅ (mg/L)	1533.0 $\pm$ 35.5	0.10 $\pm$ 0.00 (90 min)	99.99	2
TSS (mg/L)	1080 $\pm$ 20	1.0 $\pm$ 0.0 (90 min)	99.91	40
TDS (mg/L)	3715 $\pm$ 100	155 $\pm$ 3 (90 min)	95.83	1000
Total phosphorus (mg/L)	3.47 $\pm$ 0.08	< 0.01 (90 min)	99.99	0.2
NH ₃ –N (mg/L)	4.20 $\pm$ 0.10	< 0.01 (90 min)	99.99	0.1
Total Kjeldahl nitrogen (mg/L)	109.3 $\pm$ 2.2	< 0.01 (90 min)	99.99	5
Color (Pt-Co)	967 $\pm$ 17	1.0 $\pm$ 0.1 (90 min)	99.90	15
Oil and grease (mg/L)	184 $\pm$ 4	< 0.01 (90 min)	>99.99	1
Calcium (mg/L)	569 $\pm$ 6	33.2 $\pm$ 4.4 (90 min)	94.16	300
Dissolved oxygen (mg/L)	2.0 $\pm$ 0.1	7.4 $\pm$ 0.1	Increase	Minimum 6
pH	7.5 $\pm$ 0.1	7.3 $\pm$ 0.1	—	6–9

Note: $n = 3$. Benchmarks follow the river water quality standards of Government Regulation of the Republic of Indonesia No. 22 of 2021.

since the gravity-fed biological and polishing transfers add little pumping. A full operating-cost assessment is beyond what these data support, because electrode consumption, sludge handling, aeration demand, adsorbent replacement and long-term hydraulic performance were not quantified. The results therefore establish technical complementarity at laboratory scale without an accompanying economic claim.

Each 10 L batch of raw wastewater yielded about 7 L of effluent meeting all physicochemical criteria within the sampling window, a laboratory recovery of approximately 70%. Set against the reported water demand for fabric preparation,

washing, de-waxing and final rinsing, this volume could displace a corresponding share of the fresh-water drawn for those non-potable operations, while removing the wastewater-disposal charge on the volume recycled.

CONCLUSIONS

Electrocoagulation, sequential biofiltration and dual-media adsorption acted as complementary stages rather than competing options in the treatment of high-strength batik wastewater. Alternating iron and aluminum plates at 5 A and 12 V

for 30 min gave the best-balanced pretreatment, removing 56.1% of chemical oxygen demand, 60.0% of five-day biochemical oxygen demand, 76.9% of total suspended solids, 88.2% of total phosphorus, 26.2% of ammonia nitrogen, 66.5% of total Kjeldahl nitrogen, 84.0% of color, 67.4% of oil and grease and 46.6% of calcium. Total dissolved solids rose during this stage, which confirms that electrocoagulation works as load reduction and not as complete treatment. Extending the sequential anaerobic–aerobic biofilter to a total retention time of 50 h lowered chemical oxygen demand to 152.6 mg/L and five-day biochemical oxygen demand to 68.8 mg/L, values the aerobic-only reactor did not approach at any retention time tested. Layered zeolite and granular activated carbon then brought the effluent to 3.7 mg/L chemical oxygen demand, 0.10 mg/L five-day biochemical oxygen demand, 1.0 mg/L total suspended solids, 155 mg/L total dissolved solids and 1 Pt-Co of color, with phosphorus, ammonia nitrogen, Kjeldahl nitrogen and oil and grease below their reporting limits. Every physicochemical parameter evaluated fell within the Indonesian river water quality standard, and roughly 70% of the raw wastewater volume was recovered as water fit for the non-potable stages of batik production. Microbiological safety was not assessed, so the recovered water is not presented as drinking water.

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