



HOUSEHOLD-SCALE TREATMENT AS A POLLUTION-CONTROL AND RESOURCE-PROTECTION STRATEGY FOR SASIRANGAN WASTEWATER SUPPORTED BY FEASIBLE MONITORING INDICATORS

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ARTICLE INFO	ABSTRACT
Article History: Received: 3 January 2026 Revised: 11 July 2026 Accepted: 27 July 2026 Published: 15 September 2026 Keywords: Sasirangan wastewater, alum, coagulation–floculation, filtration, sedimentation	This study evaluated a reproducible household-scale treatment train for Sasirangan wastewater by assessing alum coagulation–floculation, lime neutralisation, sedimentation, and filtration, using pH, colour, and settled-sludge volume as operational indicators for decentralised monitoring and preliminary unit design. The treatment sequence comprised alum coagulation–floculation, lime-based pH neutralisation, Imhoff-glass sedimentation, and gravity filtration as a polishing step. Jar tests used 1,000 mL wastewater aliquots with ten replicates ($n = 10$). A 4% (w/v) alum stock solution was applied at 4,000 mg/L, and lime at 3,200 mg/L, both based on the initial wastewater volume. Because chemical oxygen demand, biochemical oxygen demand, total suspended solids, and dye-specific concentrations were not determined, pH and colour were treated as practical indicators rather than complete measures of regulatory compliance or pollutant removal. Data were analysed using the Statistical Package for the Social Sciences (SPSS), including Shapiro–Wilk normality testing, a one-sample t-test against a 179.2 Pt–Co comparative benchmark, and a paired t-test for pre- and post-filtration colour. Coagulation–floculation produced stable post-coagulation colour values (mean = 179.95 Pt–Co, SD = 1.48), with no significant difference from the benchmark ($t(9) = 1.598$, $p = 0.144$). Lime neutralisation increased pH from acidic post-alum conditions (mean = 4.29, SD = 0.07) to the regulatory range of 6–9 (mean = 6.54, SD = 0.09). Sedimentation supported 30 minutes as a practical retention time, whereas filtration produced no significant additional colour reduction ($t(9) = 0.827$, $p = 0.430$).

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Introduction

The textile industry generates highly coloured effluents containing synthetic dyes, salts, and auxiliary chemicals that are often persistent and difficult to degrade, thus requiring reliable pretreatment before discharge or reuse. Textile wastewater is widely recognised as a complex environmental-management problem because dye uptake during textile processing is incomplete, wastewater composition varies substantially across operations, and treatment choices must balance removal performance, cost,

operational simplicity, and residual management (Holkar *et al.*, 2016; Crini & Lichtfouse, 2019). Recent reviews by Yaseen and Scholz (2019) emphasise that the load of colour and refractory compounds from reactive dyes remains a major challenge because of their chemical stability and colloidal behaviour, which can hinder conventional clarification. Therefore, simple yet effective physico-chemical pretreatment strategies remain crucial, particularly for small and medium-scale producers in developing

countries (Juanga-Labayen *et al.*, 2022). Recent studies by Badawi *et al.* (2024) also emphasise that wastewater treatment strategies should be increasingly evaluated not only for removal performance but also for sustainability-related aspects such as chemical selection, sludge management, and the feasibility of low-cost post-treatment units in decentralised systems. When untreated or poorly managed, such effluents can pose localised pollution risks to receiving waters and undermine resource-protection efforts in dye-producing communities.

In Indonesia, the traditional textile craft of Sasirangan has been reported to generate wastewater with intense colour and quality parameters that may deviate from environmental standards in both hot and cold dyeing processes (Khair & Noraida, 2025). Laboratory studies have shown that aluminium sulfate or alum-based coagulation–flocculation can significantly reduce colour intensity in Sasirangan effluent (Noraida & Khair, 2024), making it a promising core technology for household-level treatment systems. Because household-scale treatment studies on Sasirangan wastewater remain limited, selected values from previous laboratory work may also serve as comparative study benchmarks when interpreted cautiously and not confused with regulatory discharge targets. These findings are consistent with broader regional practices for batik and textile effluents, where coagulation–flocculation is often adopted as an economical first step before advanced treatment (Zakaria *et al.*, 2023). However, evidence that explicitly connects laboratory performance to an operator-friendly, monitoring-ready design for household producers remains limited. Treatment-performance interpretation, however, depends on knowledge of the raw wastewater load. Accordingly, the present study is framed as a preliminary household-scale treatment-design and operational-monitoring assessment rather than a full physicochemical evaluation of all pollutant-load parameters.

From a regulatory perspective, the Government of Indonesia mandates that industries comply with Wastewater Quality Standards, including relevant effluent indicators,

as stipulated in Regulation of the Ministry of Environment and Forestry (MoEF) No. P.16/MENLHK/SETJEN/KUM.1/4/2019 (MoEF, 2019). This regulation requires industries to treat their effluents before discharge. However, implementation at the level of small-scale enterprises such as Sasirangan producers remains constrained by limited resources, technical capacity, and infrastructure. This situation underscores the need to develop treatment systems that are simple, low-cost, and operator-friendly while supporting compliance with legal requirements. In decentralised household settings, however, routine process control often depends on a limited set of practical, easy-to-observe indicators (Dewata *et al.*, 2024).

In this study, pH and colour are therefore treated as practical operational indicators for tracking treatment performance, rather than as a complete basis for full regulatory compliance assessment. Accordingly, these indicators support routine observations and operational decision-making in small-scale treatment settings (Dewata *et al.*, 2025). Scientifically, the effectiveness of alum is mediated by charge neutralisation and sweep flocculation, in which amorphous $\text{Al}(\text{OH})_3$ precipitates adsorb and enmesh colloidal particles and dye molecules (Jiang, 2015). Lime addition can stabilise pH, strengthen floc formation, and support sedimentation (Zakaria *et al.*, 2023). Recent international literature positions coagulation–flocculation as a workhorse for coloured wastewater treatment, either as a stand-alone process or as pretreatment, because of its relatively low chemical cost, rapid response, and compatibility with sedimentation and gravity/media filtration (Tahraoui *et al.*, 2024; Zaharia *et al.*, 2024). Nevertheless, performance is sensitive to local wastewater characteristics (e.g., dye type, ionic strength, and initial pH), reinforcing the need for context-specific evaluation and design.

Although advanced technologies such as adsorption, membranes, and advanced oxidation processes show potential, their adoption in Small and Medium-sized Enterprises (SMEs) is often limited by high capital and operational costs

and maintenance complexity (Tang, 2023). In contrast, a treatment train based on coagulation–flocculation with pH neutralisation, integrated with sedimentation and filtration, offers a strong translational strategy for household-scale application, including as a pretreatment step to reduce fouling in filtration units and improve effluent stability (Ćurić & Dolar, 2022). Experimental evidence further confirms that such pretreatment can lower TSS and colour while reducing the load on downstream processes (Yaseen & Scholz, 2019; Juanga-Labayen *et al.*, 2022). This process logic is also consistent with hybrid textile-wastewater treatment studies in which coagulation–flocculation is integrated with downstream adsorption and filtration steps to improve overall treatment performance and economic feasibility (Badawi & Zaher, 2021). For small producers, this pathway can also support day-to-day operational control, where simple measurements guide routine adjustments.

Addressing this implementation need, the present study develops a preliminary, monitoring-oriented household-scale treatment design for Sasirangan wastewater by connecting laboratory treatment results with feasible operational indicators. This study aimed to evaluate a fixed, reproducible household-scale treatment train for Sasirangan wastewater by assessing alum coagulation–flocculation, lime neutralisation, sedimentation, and filtration using pH, colour, and settled sludge volume as practical operational indicators for decentralised monitoring and preliminary unit design. The novelty of the study lies in integrating a low-complexity treatment train, the local Sasirangan wastewater context, and an explicitly stated monitoring logic that can be translated into a household-scale prototype. Accordingly, the manuscript follows a problem-gap-method-evidence-application flow: It first establishes the environmental and regulatory problem, then clarifies the study scope and operational indicators, presents the treatment sequence and statistical analysis, interprets the design implications, and finally states the practical limitations for field validation.

Materials and Methods

Study Design and Operational Indicators

This study used a laboratory-based experimental design employing a jar-test approach to evaluate a sequential treatment train for wastewater from household-scale Sasirangan textile production (Baskan & Pala, 2010; Hadary *et al.*, 2025). This study evaluated a fixed, reproducible household-scale treatment train for Sasirangan wastewater by assessing alum coagulation–flocculation, lime neutralisation, sedimentation, and filtration, using pH, colour, and settled sludge volume as practical operational indicators for decentralised monitoring and preliminary unit design.

The treatment train was organised as alum coagulation–flocculation, lime neutralisation, sedimentation, and final filtration. This structure was selected because it reflects a treatment pathway that can be practically reproduced in a household setting while still allowing laboratory control over dosage, mixing, settling, and statistical replication. The experiment tested a fixed treatment sequence under controlled conditions; it was not designed as a full multi-dose optimisation study. To improve reproducibility, the experimental workflow was defined in six linked steps: Sample homogenisation, initial operational observation, alum dosing, and two-stage mixing, lime neutralisation and pH checking, Imhoff-glass settling observation, and paired colour measurement before and after filtration. This workflow also provides the logical bridge between the laboratory experiment and the proposed household-scale unit design.

In line with the monitoring-oriented framing introduced earlier, pH and colour were treated as practical operational indicators to support routine observations in decentralised settings. Settled sludge volume over time was used as a design indicator for selecting a feasible sedimentation retention time. Table 1 summarises the operational indicators, instruments, units, and decision targets used in this study.

In this study, chemical dosages were calculated based on the initial wastewater volume before chemical addition. The alum

Table 1: Operational indicators and decision targets for decentralised observations and monitoring

Operational Indicator	Measurement Instrument/ Method	Unit	Decision Target/ Reference Used in this Study	Role in the Treatment Train (Monitoring-ready Logic)
Colour	Photometer InScienPro ZE-200 (Phot 47)	Pt–Co	Comparative study benchmark: 179.2 Pt–Co, adopted from previous Sasirangan wastewater work (Noraida & Khair, 2024) used for one-sample comparison and not treated as a regulatory discharge standard.	Baseline and post-treatment performance indicator used to characterise the raw wastewater colour condition, evaluate coagulation outcome and stability across replicates, and assess whether polishing (filtration) produces measurable change.
pH	Digital pH meter	–	Regulatory compliance range: pH 6–9	Baseline and operational control indicator used to characterise the initial raw wastewater condition and to guide lime addition to bring treated effluent into the compliance range after alum-induced acidity.
Settled sludge volume vs. time	Imhoff glass reading (0–60 min)	mL apparent settled sludge layer (per 600 mL test volume)	Design settling time identified from the plateau of settling profile (≈ 30 min)	Preliminary design/operation indicator for sedimentation; supports retention-time selection and provides an initial approximation of sludge-zone requirements before filtration.
Residual light flocs/ clarity	Gravity filtration with filter paper	–	Polishing step (clarity improvement)	Removes remaining light flocs after settling; evaluated using paired colour measurement (pre vs. post filtration).

stock solution (4% w/v) was equivalent to 40,000 mg/L; addition of 100 mL stock to 1,000 mL wastewater corresponded to an alum dose of 4,000 mg/L. The lime stock suspension (4% w/v) was also equivalent to 40,000 mg/L; addition of 8 mL stock per 100 mL wastewater corresponded to a lime dose of 3,200 mg/L. Raw wastewater characterisation in this experiment was limited to pH- and colour-based operational monitoring during the treatment sequence. Chemical Oxygen Demand (COD), Biochemical Oxygen Demand (BOD), Total Suspended Solids (TSS), and dye-specific concentrations

were not analysed and therefore limit a full evaluation of treatment performance. The value of 179.2 Pt–Co was used as a comparative benchmark derived from previous Sasirangan wastewater research (Noraida & Khair, 2024), not as a regulatory discharge limit or an arbitrary benchmark. The alum dose was a fixed design dose applied uniformly across replicates; no formal multi-dose optimisation jar test was conducted. The Imhoff reading represents the apparent settled sludge-layer volume and does not provide the solids concentration (% total solids) of the sludge.

Wastewater Source and Sampling

Wastewater samples were collected from a household-scale Sasirangan production unit in Banjarbaru, South Kalimantan, Indonesia. Field observations indicated that producing 40 pieces of fabric generated approximately 1,000 L of wastewater (≈ 25 L per piece). This production-based volume estimate was used only as the scaling basis for the proposed household-scale unit and not as a universal wastewater-generation coefficient for all Sasirangan producers. Composite samples were collected and homogenised before laboratory treatment to improve consistency across experimental runs. Each jar-test replicate was prepared from the homogenised composite sample so that differences among replicates primarily reflected treatment-response variability rather than sample-source variability.

Initial Characterisation of Raw Wastewater

Before treatment, the homogenised composite raw wastewater sample was evaluated using the operational indicators adopted in this study, namely pH and colour. However, the experiment did not generate a complete numerical raw-wastewater baseline for all pollutant-load parameters. For this reason, the analysis focuses on process-stage indicators, including pH after alum addition, pH after lime neutralisation, post-coagulation colour, settling behaviour, and pre- and post-filtration colour. The measured pH after alum addition ranged from 4.2 to 4.4 (mean = 4.29, SD = 0.07), while pH after lime neutralisation ranged from 6.4 to 6.6 (mean = 6.54, SD = 0.09). Post-coagulation colour was 179.95 Pt-Co (SD = 1.48). Because COD, BOD, TSS, and dye-specific concentrations/types were not determined, the present study does not claim a complete pollutant-removal evaluation. Instead, it provides an operational and preliminary design assessment relevant to household-scale monitoring.

Coagulation–flocculation (Jar Test)

Jar tests were conducted in jar-test vessels using an initial wastewater volume of 1,000 mL per replicate. A coagulant stock solution was prepared by dissolving 4 g of alum in 100 mL of water to obtain a 4% (w/v) alum solution, equivalent to 40 g/L (40,000 mg/L). A 100 mL aliquot of the 4% alum solution was added to each 1,000 mL wastewater replicate; therefore, the applied alum dose was 4,000 mg/L on an initial-wastewater-volume basis (4 g alum per 1.0 L wastewater). All 10 replicates were treated using the same stock concentration, dose, mixing sequence, and measurement procedure to support repeatability. A single fixed alum dose was used to evaluate the feasibility and reproducibility of the proposed treatment train under standardised laboratory conditions.

A formal jar-test optimisation across multiple alum doses was not conducted in this phase. Therefore, the selected dose should not be interpreted as an experimentally optimised or universally optimal dose for colour removal. Mixing was performed in two steps: Rapid mixing at 60 rpm for 1–2 minutes, followed by slow mixing at 30 rpm to promote floc formation and growth. Colour was measured using a Photometer InScienPro ZE-200 (Phot 47 program), and results are reported on the Pt–Co scale. Future studies should evaluate multiple alum doses across the same raw wastewater matrix to determine the dose–response relationship and identify the optimum operating window for colour reduction and process efficiency.

pH Neutralisation with Lime

Following alum coagulation–flocculation, the treated wastewater tended to become acidic. Neutralisation was therefore performed using lime. A 4% (w/v) lime suspension was prepared by dissolving 4 g of lime in 100 mL of water, equivalent to 40 g/L (40,000 mg/L), and was

dosed at 8 mL per 100 mL of initial wastewater, followed by gentle mixing. This corresponds to a lime dose of 3,200 mg/L, calculated based on the initial wastewater volume rather than the final mixture volume after alum addition. pH was measured using a digital pH meter. The operational pH target was interpreted against the regulatory compliance range (pH 6–9) (Table 1).

Sedimentation (Imhoff Glass) and Settling-time Profile

Sedimentation behaviour was evaluated using an Imhoff glass to obtain a practical settling-time profile. A 600 mL wastewater aliquot and 60 mL of the 4% alum solution were introduced into the Imhoff glass. This sedimentation test used the same alum dosing ratio as the jar test, equivalent to 4,000 mg/L on an initial-wastewater-volume basis. Settled sludge volume (mL) was read directly from the Imhoff scale as the apparent volume of the settled sludge layer accumulated at the bottom of the glass at each time point. In this study, this reading represents the bulk settled layer observed in the Imhoff glass, not the dry-solids mass and not the solids concentration (% total solids) of the sludge. The settling profile was used to identify a feasible settling time for design purposes, consistent with the reported settling-time interpretation. The solids concentration of the settled sludge (e.g., % total solids) was not determined in this laboratory phase. Therefore, the Imhoff-glass reading was used only as a preliminary settling/sludge-zone indicator and not as a complete sludge-characterisation parameter.

Filtration (Polishing Step) and Paired Measurement Structure

After clarification, filtration was performed using filter paper to remove remaining light flocs that did not settle. To match the paired statistical structure used, colour was measured for each replicate before filtration (pre-filtration) and again after filtration (post-filtration) using the same replicate sample stream. Filtration was treated as a polishing operation primarily

intended to improve clarity and remove residual flocs rather than as the main mechanism of colour reduction.

Quality Assurance, Replication, and Analytical Standards

Photometer and pH meter instruments were calibrated before measurement according to the instrument operating procedures. Each experimental condition was replicated ten times ($n = 10$) to improve reliability and to support inferential comparison. Measurements were conducted consistently across replicates, and the analytical workflow was aligned with recognised water and wastewater examination principles described in Standard Methods (APHA, AWWA, & WEF, 2023). This study emphasised the repeatability of operational indicators rather than complete physicochemical characterisation.

Statistical Analysis (SPSS)

Data were analysed using Statistical Package for the Social Sciences (SPSS) at a significance level of $\alpha = 0.05$. Data normality was assessed using the Shapiro–Wilk test. Post-coagulation colour values were compared against a comparative study benchmark of 179.2 Pt–Co, adopted from previous Sasirangan wastewater research (Noraida & Khair, 2024), using a two-tailed one-sample t-test. This benchmark was used to evaluate statistical comparability with earlier laboratory findings and was not interpreted as a discharge standard or compliance threshold. Differences between pre- and post-filtration colour values were analysed using a two-tailed paired t-test because the same replicate stream was measured before and after filtration. In addition to p values, mean differences, 95% confidence intervals, and effect-size interpretation were used to avoid relying only on statistical significance. Descriptive statistics (mean, standard deviation, minimum, and maximum) were reported for colour, pH, and sludge volume. Table 2 summarises the experimental comparisons and corresponding statistical tests.

Table 2: Experimental design and Statistical Analysis plan (SPSS)

Outcome Variable	Stage/Comparison	Design	n	Assumption Check	SPSS
Colour (Pt–Co)	Post-coagulation colour after alum dosing (4,000 mg/L based on initial wastewater volume) vs. comparative study benchmark (179.2 Pt–Co; Noraida & Khair, 2024)	Single-sample comparison	10	Shapiro–Wilk normality	One-sample t-test (two-tailed)
Colour (Pt–Co)	Pre-filtration vs. post-filtration colour	Paired comparison (same replicate before/after filtration)	10	Shapiro–Wilk normality of paired differences	Paired t-test (two-tailed)
pH	Post-coagulation pH and post-neutralisation pH after lime dosing (3,200 mg/L based on initial wastewater volume)	Operational compliance check	10	–	Descriptive statistics (compliance interpretation)
Settled sludge volume	Settled sludge volume recorded from 0–60 minutes	Time-profile observation	–	–	Descriptive trend (design basis)

Results

Wastewater Generation as the Design Basis

Observations at the household-scale Sasirangan production unit indicated that approximately 1,000 L of wastewater were generated for every 40 pieces of fabric, equivalent to ≈ 25 L per piece. This production-based estimate was used as the scaling basis for the proposed household treatment unit. More details can be seen in Figure 1.

Initial Raw Wastewater Characteristics

Before treatment, the homogenised composite raw Sasirangan wastewater was characterised using the practical operational indicators adopted in this study, namely pH and colour. A separate numerical baseline for initial raw-wastewater pH and colour was not presented, as this laboratory phase did not include a full pollutant-load characterisation. The treatment sequence was therefore interpreted using practical operational indicators measured during the process. After alum addition, pH ranged from



Figure 1: Addition of alum solution to Sasirangan wastewater

4.2 to 4.4 (mean = 4.29, SD = 0.07). After lime neutralisation, pH increased to 6.4–6.6 (mean = 6.54, SD = 0.09). Post-coagulation colour was 179.95 Pt–Co (SD = 1.48). Because COD, BOD, TSS, and dye-specific concentrations were not determined in this experiment, the treatment results presented below should be interpreted as reflecting performance in relation to these practical operational indicators rather than as a complete assessment of total pollutant-load removal. Figure 1 documents the laboratory workflow for alum dosing into replicated Sasirangan wastewater samples. The setup illustrates the practical handling of household effluent under controlled conditions and reflects the replicate-based experimental design ($n = 10$). This step represents the initial unit operation in the treatment train, where chemical addition and mixing promote colloid destabilisation and subsequent floc formation before downstream clarification.

Coagulation–flocculation, pH Neutralisation, and Sedimentation Outcomes

Jar-test coagulation-flocculation using a 4% (w/v) alum solution produced consistent colour outcomes across 10 replicates ($n = 10$). The mean post-coagulation colour value was 179.95 Pt–Co (SD = 1.48). Shapiro–Wilk testing indicated that the post-coagulation colour dataset was normally distributed ($W = 0.93$, $p = 0.470$), supporting parametric inference. A one-sample t-test comparing the post-coagulation colour mean to the comparative study benchmark of 179.2 Pt–Co (Noraida & Khair, 2024) showed no statistically significant difference ($t(9) = 1.598$, $p = 0.144$, two-tailed, $\alpha = 0.05$). The observed mean difference was small in practical terms (0.75 Pt–Co), with an estimated 95% confidence interval from -0.31 to 1.81 Pt–Co and a moderate standardised effect ($d \approx 0.51$). This result indicates that the post-coagulation colour obtained under the present laboratory conditions was statistically comparable to the benchmark level reported in previous Sasirangan wastewater work. Because a single fixed alum dose was used, interpret the finding as the

performance of the selected configuration under standardised conditions rather than as evidence that 4,000 mg/L is the optimum alum dose.

Following alum addition, the wastewater became acidic, with pH values ranging from 4.2 to 4.4 (mean = 4.29, SD = 0.07). Subsequent neutralisation with 4% (w/v) lime solution at a dose of 8 mL per 100 mL of wastewater increased pH to 6.4–6.6 (mean = 6.54, SD = 0.09). This post-neutralisation range falls within the regulatory pH compliance range (pH 6–9), indicating that lime addition effectively restored pH to a level aligned with the pH criterion.

The Imhoff-glass sedimentation test showed a clear settling progression over time. From an initial test volume of 600 mL, the apparent settled sludge-layer volume reached approximately 200 mL after 30 minutes. Expressed on the same observational basis, this is equivalent to approximately 333 mL of apparent settled layer per litre of tested wastewater. This value should be interpreted as an Imhoff-glass reading of the bulk settled layer rather than as the volume of dry solids or the solids concentration of the sludge.

At 60 minutes, the measured settled sludge volume was approximately 180 mL. This apparent decrease relative to the 30-minute reading is interpreted as sludge compaction/consolidation rather than a reduction in the mass of settled solids. In other words, the settled layer became denser between 30 and 60 minutes, resulting in a smaller occupied volume in the Imhoff glass. This pattern indicates that most settleable solids had already accumulated by around 30 minutes, whereas the subsequent change mainly reflected compaction of the settled sludge layer. This settling behaviour supports the use of ~30 minutes as a practical sedimentation retention time for unit design. Because the solids concentration of the settled sludge was not measured, the reported Imhoff reading should be used only as a preliminary indicator of sludge-layer formation and approximate sludge-zone requirement, rather than as a complete basis for detailed sludge-handling design.

Filtration as a Polishing Step (Paired Comparison)

Filtration was applied after clarification to remove remaining light flocs, as shown in Figure 2.

Figure 2 shows a simple gravity filtration arrangement used as a post-clarification polishing step. The images illustrate the removal of residual light flocs and improved apparent clarity. This supports the role of filtration in removing residual flocs after settling rather than serving as the primary driver of colour reduction. Colour measurements before and after filtration (paired within the same replicate stream) indicated minimal change attributable to filtration. The mean difference between pre- and post-filtration colour values was approximately 0.4 Pt-Co. A paired t-test confirmed that the difference was not statistically significant ($t(9) = 0.827$, $p = 0.430$, two-tailed, $\alpha = 0.05$). The estimated 95% confidence interval for the paired difference ranged from -0.70 to 1.50 Pt-Co, and the paired effect size was small ($d_z \approx 0.26$), supporting the interpretation that filtration functioned mainly as a polishing step rather than a major colour-removal stage.

This finding indicates that filtration primarily functioned as a polishing step for residual floc removal and apparent clarity,

rather than producing an additional statistically significant reduction in colour concentration. Accordingly, the contribution of filtration in this treatment train should be interpreted as physical polishing after clarification, not as the main mechanism of colour removal. To provide a consolidated view of the statistical outputs produced in SPSS (normality testing, one-sample and paired t-tests, and descriptive summaries), the key results are summarised in Table 3.

Table 3 consolidates the key statistical results and clarifies how to interpret each indicator. The benchmark value of 179.2 Pt-Co was adopted from previous Sasirangan wastewater research (Noraida & Khair, 2024) and was used only for comparative one-sample testing. It was not interpreted as a regulatory discharge standard or an arbitrary performance target. The lower apparent settled sludge volume at 60 minutes relative to 30 minutes is interpreted as sludge compaction rather than a loss of settled solids. Therefore, the reported settled-sludge values should be read as Imhoff-glass observations of apparent settled-layer volume, not as dry-solids concentration or percentage total solids.



Figure 2: Water filtration to remove light flocs

Table 3: Summary of key results and statistical outputs (SPSS)

Indicator	Stage/Comparison	n	Result (mean $\pm$ SD/range)	Statistical Output (Two-tailed, $\alpha = 0.05$)
Colour (Pt–Co)	Post-coagulation colour	10	179.95 $\pm$ 1.48	Shapiro–Wilk: W = 0.93, $p = 0.470$
Colour (Pt–Co)	Post-coagulation vs. comparative study benchmark (179.2 Pt–Co; Noraida & Khair, 2024)	10	–	One-sample t-test: t(9) = 1.598, $p = 0.144$
pH	After alum addition	10	4.29 $\pm$ 0.07 (4.2–4.4)	Descriptive (operational indicator)
pH	After lime neutralisation	10	6.54 $\pm$ 0.09 (6.4–6.6)	Descriptive; within pH 6–9 criterion
Settled sludge volume	Imhoff glass (30 min)	–	~200 mL apparent settled sludge layer per 600 mL test volume	Descriptive settling profile (design basis)
Settled sludge volume	Imhoff glass (60 min)	–	~180 mL apparent settled sludge layer per 600 mL test volume	Apparent decrease attributable to sludge compaction/consolidation of the settled layer
Colour (Pt–Co)	Pre- vs. post-filtration	10	Mean difference $\approx$ 0.4 Pt–Co	Paired t-test: t(9) = 0.827, $p = 0.430$ (not statistically significant)

Proposed Household-scale Treatment Unit Design

Based on the observed responses across sequential unit operations—coagulation, flocculation, pH neutralisation, sedimentation (with a practical retention time of ~ 30 minutes), and filtration as polishing, a household-scale treatment unit was proposed. For a household batch of 1,000 L wastewater, the laboratory design doses applied in this study are equivalent

to 4.0 kg alum and 3.2 kg lime. In practical field implementation, these doses would be more feasibly applied as pre-weighed masses or equivalent calibrated dosing aids, rather than by directly reproducing the laboratory stock-solution preparation format. Figure 3 presents the conceptual design, showing the intended process order before final discharge.

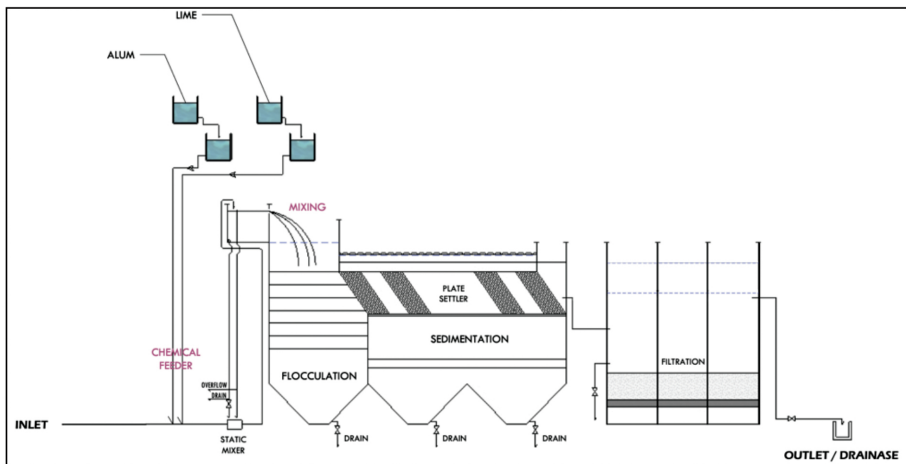


Figure 3: Design of the Sasirangan wastewater treatment unit

A key limitation of the present study is that the raw wastewater was characterised directly within the experiment using only practical operational indicators, namely initial pH and colour. A more comprehensive evaluation of treatment performance and pollutant removal efficiency would require parameters such as COD, BOD, TSS, and dye-specific concentrations. Figure 3 shows the proposed household-scale configuration integrating chemical dosing (alum and lime), mixing/flocculation, sedimentation/clarification, and final filtration. The design logic follows the experimental sequence: Alum is added first to destabilise coloured colloidal and particulate fractions, lime is added next to restore pH, sedimentation provides the main floc-separation stage, and filtration acts as a final polishing barrier for residual light flocs. Drainage points are included because sludge removal is an operational requirement, not a secondary detail. Overall, the design translates the laboratory findings into a practical process arrangement while retaining the study's limitation that broader pollutant-load indicators still require future validation.

Discussion

The discussion is organised around three linked issues: Treatment performance, process mechanism, and field-implementation feasibility. First, the results demonstrate that alum coagulation–flocculation followed by lime neutralisation, sedimentation, and filtration can provide a low-complexity treatment pathway for household-scale Sasirangan wastewater under controlled laboratory conditions. The process achieved stable post-coagulation colour outcomes across replicates, restored pH into the regulatory range after neutralisation, and identified an operationally feasible settling time of approximately 30 minutes. Filtration mainly acted as a polishing step rather than a primary colour-removal mechanism. These findings support using pH and colour as practical operational indicators for decentralised observations, while also confirming that the study should not be interpreted as a complete

assessment of treatment performance across all wastewater quality parameters.

A further limitation of the present study is that alum coagulation was tested using a single fixed dose under standardised laboratory conditions. This approach was appropriate for evaluating the reproducibility of the proposed household-scale treatment sequence, but it does not establish an optimum alum dose for Sasirangan wastewater. Because coagulation performance is sensitive to raw wastewater characteristics, future work should include multi-dose jar-test optimisation to determine the most effective and efficient dose range for colour reduction and broader treatment objectives.

The comparative use of 179.2 Pt–Co in the present study should also be interpreted carefully. This value was not used as a discharge standard, but as a benchmark derived from previous Sasirangan wastewater work (Noraida & Khair, 2024) to evaluate whether the post-coagulation colour obtained here was statistically comparable to an earlier laboratory reference level. Because the study was designed as a household-scale operational-monitoring and preliminary design assessment, this comparative benchmark helped contextualise the observed post-treatment colour outcome without overstating its regulatory relevance.

These findings are consistent with prior work on textile wastewater treatment using batch coagulation–flocculation systems, which can reduce colour intensity (Rusydi *et al.*, 2017). Studies on batik wastewater also report that alum coagulation–flocculation can reduce COD, turbidity, colour, and TSS, supporting its role as an economical first-line treatment (Daud *et al.*, 2023). In addition, industrial-scale evaluations of alum combined with lime show that lime increases alkalinity, shifts the system toward an optimal pH window for aluminium hydrolysis, and promotes the formation of denser, more readily settleable flocs (Quintero *et al.*, 2024). In the present context, pH restoration after alum addition is particularly relevant for compliance-oriented operation, because pH is both a regulatory parameter and a practical

field-measurable indicator for decentralised monitoring.

In more advanced textile treatment trains, coagulation–flocculation is widely used as a pretreatment step to reduce the burden on downstream processes and lower overall costs, often followed by filtration as a refinement stage (Dobrosz-Gómez *et al.*, 2024). Comparisons with electrochemical treatment of Tunisian textile wastewater further suggest that alum-based chemical coagulation remains competitive for reducing colour intensity or TSS when cost efficiency and operational simplicity are the main priorities. These conditions closely match household-scale applications (Gasmi *et al.*, 2022). Moreover, coagulation pretreatment reduces solids loading to subsequent units, helping to limit sediment accumulation and stabilise downstream sedimentation and filtration performance (Aragaw & Bogale, 2023). This interpretation aligns with the Results, in which post-filtration colour changed only minimally, and the paired comparison was not statistically significant. This indicates that filtration primarily improved apparent clarity by removing residual flocs after upstream chemical treatment and settling, rather than producing a meaningful additional reduction in colour. Taken together with the post-coagulation colour result, this pattern suggests that the residual colour after coagulation was predominantly associated with dissolved or fine colour-causing constituents that were not effectively removed by simple gravity filtration. Thus, the remaining colour after coagulation and filtration is more likely attributable to soluble residual chromophores than to settleable or filterable floc particles alone.

Mechanistically, alum hydrolyses to form amorphous $\text{Al}(\text{OH})_3(\text{s})$, which provides adsorptive surfaces and enables charge neutralisation and sweep flocculation of colloidal particles and charged dye molecules (particularly sulfonated dyes) (Kabdaşlı *et al.*, 2015; Madeira *et al.*, 2023). Lime addition raises pH and alkalinity, promoting the formation of larger and denser flocs, while facilitating co-precipitation

with divalent cations (Ca^{2+}) and sulfate anions derived from alum. Under sufficiently alkaline conditions, calcium–aluminium–sulfate phases can form and contribute to pollutant sweeping and co-removal pathways (Kabdaşlı *et al.*, 2015; Madeira *et al.*, 2023). In practical terms, this chemistry supports the observed sequence in the Results: Alum-induced acidification followed by lime-driven pH restoration and improved settleability, which together provide an operationally controllable pathway using simple measurements (pH and colour).

Despite these mechanisms, the residual post-coagulation colour of approximately 180 Pt–Co suggests that not all colour-causing constituents were removed by coagulation alone. The remaining colour is most plausibly attributed to dissolved or weakly destabilised chromophoric compounds, including dye fractions that remained in the aqueous phase after charge neutralisation and sweep flocculation. In other words, alum coagulation effectively destabilised and removed the more settleable and flocculable fraction of the coloured wastewater, but was less effective for residual soluble colour that was not readily incorporated into the formed flocs.

This interpretation is consistent with the role of coagulation–flocculation as a strong clarification and bulk colour-reduction step, but not necessarily a complete removal mechanism for all dissolved colour bodies in textile wastewater. The persistence of residual colour may also reflect wastewater-specific factors such as dye chemistry, ionic strength, and the fixed coagulant dose applied in this study. Because the present experiment used a single fixed alum dose and did not include a formal dose-optimisation matrix, the residual colour should not be interpreted as evidence of coagulation failure, but rather as an indication that a remaining dissolved colour fraction likely persisted under the tested operating conditions.

Mixing intensity and duration are also critical for process effectiveness. Rapid mixing increases collision frequency and promotes charge neutralisation, while slow mixing supports floc growth and aggregation, thereby

enhancing sedimentation rates (Vadasarukkai & Gagnon, 2017; Mustereț *et al.*, 2021). Subsequently, sedimentation separates flocs via hindered/zone settling at higher solids concentrations; in this context, settleable solids characterisation using an Imhoff cone provides a practical indicator of load reduction before filtration (Sibiya *et al.*, 2021). The settling profile observed in this study showed that most settleable solids had accumulated by around 30 minutes, while the lower settled sludge volume observed at 60 minutes is interpreted as compaction/consolidation of the settled sludge layer rather than a reduction in settled solids. Accordingly, a retention time of ~30 minutes is considered design-relevant because it captures the main settling phase while avoiding unnecessary extension of detention time in a small-scale treatment unit.

With respect to filtration, pre-coagulated water typically produces slower head loss development and lighter fouling in both conventional granular filters and membrane systems (Aragaw & Bogale, 2023). For Micro, Small, and Medium Enterprises (MSMEs), Slow Sand Filtration (SSF) is a low-cost polishing option with stable operation once coagulation–flocculation has reduced colloid loads (Maiyo *et al.*, 2023). The relevance of a polishing step after coagulation is further supported by hybrid wastewater-treatment studies showing that post-coagulation filtration can contribute to overall process refinement even when the main reduction in colour is achieved upstream (Badawi & Zaher, 2021). In addition, low-cost filter materials derived from agricultural residues, such as modified rice husk, have been proposed as practical options for decentralised wastewater polishing and reuse-oriented systems (Badawi *et al.*, 2024).

In the present results, filtration did not significantly change colour values, which supports its role as a polishing barrier for residual flocs rather than a primary removal step for dissolved/colloidal colour. Sludge management also requires attention because alum–lime treatment generates mineral-rich sludge; its

handling, disposal, and any potential beneficial use should be assessed to avoid transferring pollution burdens from liquid effluent to solid residuals (Yulius *et al.*, 2024). This sustainability dimension is increasingly emphasised in recent water-treatment literature, where sludge-derived streams and residuals are discussed not only as disposal problems but also as potential targets for reuse and zero-waste process design when technically feasible (Badawi & Hassan, 2024). This aspect is directly relevant to resource protection and pollution control, particularly where household producers may lack formal sludge disposal pathways (Putra *et al.*, 2024). Because direct raw wastewater characterisation in this experiment was limited to initial pH and colour, the present conclusions should be interpreted as operational and design-oriented rather than as a complete evaluation of overall pollutant-load removal.

The relatively large settled sludge-layer reading observed in the Imhoff glass should also be interpreted cautiously. In this study, the reported value represents the apparent bulk volume of the settled sludge layer in the glass, not the dry-solids content and not the solids concentration (% total solids) of the sludge. Accordingly, the reading provides a useful preliminary indication that sludge accumulation may be substantial under the tested coagulation conditions. However, it should not be treated as a complete sludge-production parameter for engineering design. More detailed sludge characterisation, including solids concentration and dewaterability, would be required before finalising the sludge-handling zone of a full-scale or field prototype unit. Because the present study did not determine the % total solids, the sludge-zone implication of the Imhoff reading should be regarded as conservative and preliminary rather than definitive.

Theoretically, these results reinforce conceptual models of interparticle interactions in anionic dye systems. Charge neutralisation and capture by $\text{Al}(\text{OH})_3$ gels, together with Ca–Al-associated phases at elevated pH, can explain colour reduction without reliance on advanced

technologies (Madeira *et al.*, 2023; Quintero *et al.*, 2024). At the same time, the persistence of residual colour after coagulation indicates that not all chromophoric species were equally amenable to destabilisation and floc capture under the applied conditions. This is particularly plausible for dissolved dye fractions or low-molecular-weight coloured compounds that remain in solution after the more flocculable fraction is removed.

Practically, the tested process matches MSME constraints because the chemicals are readily available, simple pH and colour checks can guide the process, and modular filtration can be implemented as a polishing step. However, laboratory-to-household translation remains conditional on wastewater variability, temperature effects, operator skill, chemical supply, and routine sludge management. These constraints define the next stage of validation rather than weakening the preliminary design contribution of the study.

For practical field translation, the laboratory design doses used in this study correspond to 4.0 kg alum and 3.2 kg lime for a 1,000 L wastewater batch, calculated from the applied doses of 4,000 mg/L alum and 3,200 mg/L lime on an initial-wastewater-volume basis. At the household scale, this mass-based expression is more operationally practical than directly scaling up the 4% stock-solution format used in the laboratory, because preparing very large stock-solution volumes for a 1,000 L batch would be cumbersome for routine use. Accordingly, a householder would more feasibly measure the chemicals using pre-weighed amounts (e.g., 4.0 kg alum and 3.2 kg lime per 1,000 L batch), then dissolve or slurry them in separate containers before adding them to the treatment tank. Where weighing facilities are limited, simplified dosing aids such as pre-packed dose units, calibrated scoops, or marked dosing containers should be considered in future prototype development to reduce operator error and improve repeatability.

These anticipated constraints indicate that field validation is needed not only to confirm treatment performance under real variations

in wastewater composition, temperature, and household operation, but also to determine whether the dosing procedure can remain sufficiently simple, accurate, and robust for routine application. Future studies should therefore develop a prototype and conduct field testing under actual household conditions, while broadening the monitoring set beyond pH and colour, where feasible, to include parameters such as TSS and COD, and evaluating sludge-handling options to avoid shifting pollution burdens from liquid effluent to solid residues (Madeira *et al.*, 2023).

Further work should therefore evaluate not only broader parameters such as COD and TSS, but also the extent to which residual post-coagulation colour is associated with dissolved dye fractions and whether dose optimisation or complementary post-treatment steps are needed to reduce this remaining colour fraction more effectively.

Conclusions

This study demonstrates that a simple, low-cost treatment train combining alum coagulation–flocculation, lime-based pH neutralisation, sedimentation, and filtration can provide stable operational outcomes for Sasirangan textile wastewater under controlled laboratory conditions. The post-coagulation colour value was statistically comparable to the selected benchmark; lime addition restored pH to the regulatory range of 6–9, and the sedimentation profile supported approximately 30 minutes as a practical retention time. Filtration improved apparent clarity by removing residual light flocs, but it did not produce an additional statistically significant reduction in colour. The proposed treatment train is therefore best interpreted as a household-scale pretreatment and operational-monitoring approach guided by feasible indicators such as pH and colour, not as a complete regulatory-compliance assessment. The study also identifies important limitations: COD, BOD, TSS, dye-specific concentrations, sludge solids concentration, and field operating variability were not evaluated.

For field application, the laboratory design doses correspond to 4.0 kg alum and 3.2 kg lime per 1,000 L wastewater batch. However, the practicality, dosing accuracy, operator consistency, sludge handling, and long-term performance of this approach require prototype-based field validation. Future studies should broaden monitoring to include COD, BOD, TSS, residual dye fractions, and sludge characteristics so that the treatment train can be assessed more comprehensively before full household-scale implementation.

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Conflict of Interest Statement

The authors agree that this research was conducted without any self-benefit, commercial, or financial conflicts and declare no conflicts of interest with the funders.

Author Contributions Statement

AK conducted the research, wrote, revised, reviewed, and approved the article submission. SA formulated the main research idea and provided the theoretical framework. N designed the research and supervised its progress.

Data Availability Statement

The data supporting the findings of this study are available from the corresponding author upon reasonable request.

Ethical Conduct

All information communicated in this article does not require ethical approval or informed consent because human or animal subjects were not involved.

Declaration of AI-usage

During the preparation of this work, the authors used AI tools to improve grammar and clarity. In using the AI tools, the authors reviewed and edited the content as needed and bear full responsibility for the content of this manuscript.

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