

Synergistic Coagulation-Adsorption of Methyl Orange Dye Using DCD-F Resin and PAC-AC-CP Composite: Mechanisms and Techno-Economic Performance

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Abstract

This study investigated the synergistic removal of methyl orange (MO) dye from synthetic textile wastewater using an integrated coagulation-adsorption system comprising dicyandiamide-formaldehyde (DCD-F) resin and a composite of polyaluminium chloride (PAC), activated carbon (AC), and cationic polymer (CP), denoted PAC-AC-CP, at a 70:25:5 mole ratio. Batch experiments were conducted using a conventional jar test to optimise DCD-F resin dosage and rapid mixing speed. The optimum conditions of 120 ppm DCD-F resin, 250 ppm PAC-AC-CP composite, and 180 rpm rapid mixing achieved 99% MO dye removal, reducing the colour value from 1622 ± 14.00 to 9 ± 2.02 ADMI. The final colour value was below the Malaysian industrial effluent discharge limits for Standard A and Standard B. Kinetic analysis showed that the pseudo-second-order (PSO) model provided the best fit, with R^2 values above 0.999. Field emission scanning electron microscopy (FESEM) showed rough, porous, and aggregated flocs, while Fourier transform infrared (FTIR) spectroscopy indicated functional group interactions between MO dye and the treatment agents. Zeta potential shifted from -20.6 to $+5.62$ mV, supporting charge neutralisation and particle destabilisation. The findings indicate that MO dye removal involved charge neutralisation, adsorption, interparticle bridging, and sweep flocculation. A preliminary techno-economic analysis estimated a treatment cost of USD 0.5429/m³ at a capacity of 1,000 m³/day, indicating the potential of the proposed system for effective and economically feasible textile wastewater treatment.

1 Introduction

The escalating generation of industrial wastewater exceeds 360 billion m³ annually and poses a threat to environmental sustainability (Kato & Kansha, 2024). Wastewater from the textile industry is a major contributor because it contains large amounts of persistent synthetic dyes. Synthetic dyes such as azo dyes have replaced an estimated 50–70% of natural dyes due to their low production cost and high effectiveness (Shapiro, 2026; Zahuri et al., 2023). This class of pollutants includes compounds such as direct blue 1, direct red 28, acid black 1, acid orange 1, acid red 88 and mordant yellow. Methyl orange (MO) dye is a commonly used anionic mono-azo dye that accounts for 25–40% of industrial applications (Hambisa et al., 2023; Pandey et al., 2024). MO dye is a hazardous organic pollutant that requires removal due to its complex aromatic structure and high chemical stability. Its presence in wastewater can reduce light penetration, disrupt photosynthetic processes and affect aquatic ecosystems. In addition, MO dye and its degradation by-products may pose health risks to humans, including respiratory disorders, skin irritation, carcinogenic effects and organ toxicity (Kazemi et al., 2026). Textile wastewater in Malaysia has been reported to exhibit colour values ranging from 352 to 3743 ADMI, which can exceed the Malaysian industrial effluent discharge limits (Daud et al., 2023; Department of Environment Malaysia, 2009). Therefore, an effective treatment method is required to reduce MO dye colour before wastewater discharge.

This study applies an integrated coagulation-adsorption method to address the limitations of conventional treatment methods such as biological degradation and membrane filtration. These methods may involve high operational costs, long treatment periods or membrane fouling (Phillip et al.,

2026). Coagulation and adsorption are commonly applied in wastewater treatment because of their relatively simple operation and potential for scale-up (Badawi & Zaher, 2021). Dicyandiamide-formaldehyde (DCD-F) resin is used as a decolouring agent because its cationic functional groups can interact with negatively charged dye molecules and promote charge neutralisation (Karyab et al., 2023). However, DCD-F resin alone may not achieve complete MO dye removal. For example, Karyab et al. (2023) reported 70.50% dye removal using DCD-F resin at pH 7.18. Polyaluminium chloride (PAC), activated carbon (AC) and cationic polymer (CP) also have individual limitations. PAC may require relatively high dosages that increase sludge production (Islam & Mostafa, 2020), while the cost of AC can limit its large-scale application (Mukherjee et al., 2022). Therefore, combining these treatment agents may improve MO dye removal by integrating charge neutralisation, adsorption and floc formation within a single treatment system.

Previous studies have mainly focused on individual treatment agents or limited combinations for dye removal. Consequently, the performance of integrated systems combining DCD-F resin with PAC, AC and CP remains insufficiently investigated for MO dye removal. In the proposed system, DCD-F resin and PAC promote charge neutralisation and particle destabilisation, while CP supports interparticle bridging and AC provides adsorption sites for residual MO dye. Although these mechanisms may occur simultaneously, the interactions between coagulation and adsorption within an integrated DCD-F resin and PAC-AC-CP system are not yet well understood. In particular, limited studies have examined the changes in surface charge, floc morphology and functional group interactions associated with MO dye removal (Chen et al., 2024). Furthermore, limited information is available on the treatment cost and potential industrial scalability of integrated coagulation-adsorption systems for the treatment of wastewater containing MO dye. These gaps indicate the need for a combined evaluation of treatment performance, removal mechanisms and economic feasibility.

Therefore, this study investigates the synergistic use of DCD-F resin and a PAC-AC-CP composite for MO dye removal from synthetic textile wastewater. The PAC-AC-CP composite consisted of PAC, AC and CP at a 70:25:5 mole ratio, which was selected through preliminary screening based on MO dye removal efficiency. The study first evaluates the effects of DCD-F resin dosage and rapid mixing speed on MO dye removal. In order to evaluate the kinetic behaviour of MO dye colour removal, pseudo-first-order (PFO) and pseudo-second-order (PSO) kinetic models are implemented. The removal mechanism is further examined using field emission scanning electron microscopy (FESEM), Fourier transform infrared (FTIR) spectroscopy, and zeta potential analysis to assess floc morphology, functional group interactions, and surface charge behaviour. Ultimately, a preliminary techno-economic analysis is conducted to evaluate the economic feasibility of the optimised treatment system at a conceptual industrial scale. Overall, this study aims to evaluate the treatment performance, removal mechanisms, and potential larger-scale application of the integrated DCD-F resin and PAC-AC-CP system for MO dye wastewater treatment.

2 Materials and Methods

2.1 Preparation of Materials

DCD-F resin, procured from Yixing Bluwat Chemicals, Yixing, Jiangsu, China, was utilised as the primary decolouring agent. The PAC-AC-CP composite consisted of PAC, AC and CP at a mole ratio of 70:25:5. The ratio was selected following preliminary screening of different PAC, AC and CP combinations based on MO dye colour removal efficiency. The PAC-AC-CP composite was prepared and supplied as a pre-blended material by the industrial partner.

2.2 Preparation of Synthetic Textile Wastewater

Synthetic textile wastewater was prepared under controlled conditions to simulate the main characteristics of actual textile wastewater, including organic load, suspended solids, surfactant content and salinity. All chemicals were of analytical grade and purchased from Sigma-Aldrich, St. Louis, MO, USA, and were used without further purification. The chemical composition of the synthetic textile wastewater is presented in Table 1.

An MO dye stock solution of 1000 mg/L was prepared by dissolving 1 g of MO dye in 1 L of distilled water. The synthetic textile wastewater was prepared by dissolving the required chemical components listed in Table 1 in 1 L of deionised water. Starch was used as the source of total suspended solids (TSS), while acetic acid was used as the source of chemical oxygen demand (COD). Sodium lauryl sulphate was added to assist MO dye dispersion. The remaining chemicals were added for pH and salinity adjustment. An appropriate volume of the MO dye stock solution was then added to obtain a final MO dye concentration of 5 mg/L. The prepared synthetic textile wastewater was stored in airtight amber glass bottles at 4°C prior to use according to the standard preservation practices recommended by the American Public Health Association (APHA, 2017).

Table 1
Chemical composition of synthetic textile wastewater containing MO dye based on Abdullah and Jael (2019)

Substances	Chemical Formula	Concentration (mg/L)	Purpose
Starch	$(C_6H_{10}O_5)_n$	1000	Source of TSS
Acetic acid	CH_3COOH	200	Source of COD
Sucrose	$C_{12}H_{22}O_{11}$	600	Organic carbon source
Hydrochloric acid	HCl	300	pH adjustment
Sodium lauryl sulphate	$CH_3(CH_2)_{11}OSO_3Na$	100	MO dye dispersion
Sodium hydroxide	NaOH	500	pH adjustment
Sodium chloride	NaCl	3000	Salinity adjustment
Sodium carbonate	Na_2CO_3	500	pH fixation
MO dye	-	5 mg/L (1622 ± 14.00 ADMI)	Colour source

2.3 Optimisation of Coagulation-Adsorption Process

A batch study was conducted using a conventional jar test apparatus to evaluate the effects of DCD-F resin dosage and rapid mixing speed on MO dye colour removal. The overall experimental procedure is shown in Fig. 1. A 500 mL volume of synthetic textile wastewater was transferred into each beaker. DCD-F resin was added at dosages ranging from 40 to 200 ppm, while the PAC-AC-CP composite dosage was fixed at 250 ppm. The selected DCD-F resin dosage range and rapid mixing speeds were based on preliminary screening and operating conditions reported for textile wastewater treatment (Eslami & Zarei Mahmoudabadi, 2022; Karyab et al., 2023). The wastewater pH was maintained at 9 because this condition provided the highest MO dye removal efficiency during preliminary pH optimisation.

The coagulation and adsorption processes occurred simultaneously within the same batch system. DCD-F resin and PAC promoted charge neutralisation and destabilisation of MO dye molecules, while AC provided adsorption sites for residual MO dye. CP assisted floc formation through interparticle bridging. Therefore, no separate adsorption stage was applied during the jar test.

Rapid mixing was conducted at 120, 150 and 180 rpm for 1 min to disperse the treatment agents throughout the wastewater. This was followed by slow mixing at 45 rpm for 15 min to promote floc formation. The suspension was then allowed to settle for 30 min. After settling, the supernatant was collected for subsequent analysis. All experiments were conducted in triplicate, and the results are presented as the mean $\pm$ standard deviation.

2.4 Analytical Method

The treatment performance was evaluated based on MO dye removal through colour reduction. The colour of the synthetic textile wastewater was measured in ADML units using an ultraviolet-visible (UV-Vis) spectrophotometer (DR6000, Hach Company, USA) at a maximum absorbance wavelength of 464 nm. The solution pH was measured using a calibrated pH meter (pH 2700, Eutech Instruments, Singapore) throughout the experiments. The percentage MO dye colour removal was calculated using Eq. (1).

$$Removal (\%) = \left(\frac{C_i - C_f}{C_i} \right) \times 100 \quad (1)$$

where C_i and C_f represent the initial and final colour values of MO dye in ADML, respectively.

2.5 Kinetic Study of MO Dye Colour Removal

The kinetic study was conducted to evaluate the removal behaviour of MO dye during the integrated coagulation-adsorption process. DCD-F resin dosages ranging from 40 to 200 ppm were evaluated with a fixed PAC-AC-CP composite dosage of 250 ppm. The treatment was conducted under the optimised operating conditions. Samples were collected at predetermined contact times from 0 to 60 min, and the residual MO dye colour was measured in ADML units. The MO dye colour removed at time t (R_t) and at equilibrium, (R_e) was calculated using Equations (2) and (3).

$$R_t = C_0 - C_t$$

2

$$R_e = C_0 - C_e$$

3

where R_t and R_e represent the MO dye colour removed at time (t) and at equilibrium in ADML, respectively. C_0 is the initial MO dye colour value, while C_t and C_e are the residual MO dye values at time (t) and at equilibrium, respectively.

The experimental data were fitted using the pseudo-first-order (PFO) and pseudo-second-order (PSO) kinetic models to determine the model that best described MO dye colour removal behaviour. The differential and linear forms of the PFO model are expressed in Equations (4) and (5).

$$\left(\frac{dR_t}{dt} \right) = k_1 (R_e - R_t)$$

4

$$\ln (R_e - R_t) = \ln (R_e) - k_1 t$$

5

where k_1 is the PFO rate constant (min^{-1}), and t is the contact time (min).

The differential and linear forms of the PSO model are expressed in Equations (6) and (7).

$$\left(\frac{dR_t}{dt} \right) = k_2(R_e - R_t)^2$$

6

$$\frac{t}{R_t} = \frac{1}{(k_2 R_e^2)} + \frac{t}{R_e}$$

7

where k_2 is the PSO rate constant ($\text{ADMI}^{-1} \text{ min}^{-1}$). The coefficient of determination (R^2) and the agreement between the experimental and calculated R_e values were used to evaluate the goodness of fit of the kinetic models.

2.6 Characterisation Techniques for Mechanism Elucidation

The flocs formed under the optimised treatment conditions were collected after the settling stage, rinsed with deionised water and freeze-dried for 24 h prior to characterisation. The surface morphology and structure of the dried flocs were examined using FESEM (JSM-7600F, JEOL, Japan). Prior to analysis, the samples were sputter-coated with a thin platinum layer to minimise surface charging during imaging (Boukra et al., 2026).

Functional group interactions between MO dye and the treatment agents were analysed using FTIR spectroscopy (Spectrum Two, PerkinElmer, USA). The spectra were recorded over a wavenumber range of $4000\text{--}400 \text{ cm}^{-1}$ to identify changes in the functional groups associated with the treatment process (Boukra et al., 2026).

The surface charge behaviour of the wastewater before and after treatment was evaluated using a Zetasizer Nano ZSP (Malvern Panalytical, United Kingdom). Zeta potential measurements were used to assess charge neutralisation and colloidal destabilisation during floc formation.

2.7 Techno-Economic Analysis

A preliminary techno-economic analysis was conducted to evaluate the economic feasibility of the integrated DCD-F resin and PAC-AC-CP treatment system at an industrial treatment capacity of $1,000 \text{ m}^3/\text{day}$. The analysis included capital expenditure (CAPEX) and operational expenditure (OPEX). The cost assessment was based on the optimised treatment conditions obtained in this study and the scale-

up approach reported by Mahmoud et al. (2021). The system was assumed to operate for 365 days per year. All costs were expressed in USD per cubic metre of treated wastewater.

2.7.1 Capital Expenditure (CAPEX)

CAPEX included the estimated procurement and installation costs of the main treatment units. These units consisted of the equalisation tank, coagulation-adsorption/flocculation unit, sedimentation tank and dual-media filtration unit. The annualised CAPEX was calculated by dividing the total CAPEX by the annuity factor (AF), as shown in Eq. (8).

$$C_{CAPEX, annual} = \frac{C_{CAPEX, total}}{AF}$$

8

The annuity factor was calculated using Eq. (9), where r is the annual interest rate and n is the assumed system lifetime. A system lifetime of 15 years was applied because it falls within the 8–20-year useful-life range for plant and machinery specified in Malaysian Government accounting guidance (Accountant General's Department of Malaysia, 2022). An annual interest rate of 6% was adopted, giving an annuity factor of 9.712. The annual treatment capacity was calculated based on a treatment flow of 1,000 m³/day operating for 365 days per year (Eq. 10).

$$AF = \frac{(1 - (1 + r)^{-n})}{r}$$

9

$$Q_{annual} = Q_{daily} \times 365$$

10

2.7.2 Operational Expenditure (OPEX)

OPEX included chemical consumption, energy consumption, maintenance and labour costs. Chemical costs were calculated using the optimised dosages of 120 ppm DCD-F resin and 250 ppm PAC-AC-CP composite. The industrial chemical prices provided by Eco Solution Services Sdn Bhd were converted from Malaysian Ringgit to USD using an exchange rate of USD 1 = RM4.0555 reported by Bank Negara Malaysia on August 2026. The converted prices were USD 1.47/kg for DCD-F resin and USD 0.57/kg for the PAC-AC-CP composite. The chemical costs per cubic metre of treated wastewater were calculated using Equations (11) and (12).

$$C_{DCD-F} = D_{DCD-F} \times P_{DCD-F}$$

11

$$C_{PAC-AC-CP} = D_{PAC-AC-CP} \times P_{PAC-AC-CP}$$

12

where C is the chemical cost in USD/m³, D is the chemical dosage in kg/m³, and P is the unit chemical price in USD/kg.

Energy cost was estimated from the electricity required for mechanical mixing during rapid mixing at 180 rpm and slow mixing at 45 rpm. The estimated electricity consumption was 0.8776 kWh/m³ of treated wastewater. The electricity tariff was based on the Malaysian Low Voltage Industrial Tariff (Tariff ID1) of RM0.376/kWh, effective from July 2025, as reported by the Energy Commission Malaysia. The tariff was converted to USD using an exchange rate of USD 1 = RM4.0555 reported by Bank Negara Malaysia on August 2026, corresponding to approximately USD 0.0927/kWh. Based on these values, the estimated energy cost was USD 0.0814/m³ of treated wastewater.

Labour cost was estimated for one technician and three support workers. The labour rates were converted from Malaysian Ringgit to USD using an exchange rate of USD 1 = RM4.0555 reported by Bank Negara Malaysia on August 2026. The technician salary was estimated at USD 611.01/month, while each support worker was paid USD 3.91/h. Following the labour-time assumption adopted by Mahmoud et al. (2021), each support worker was assumed to work 60 h/week and 4 weeks/month. This resulted in an estimated annual labour cost of USD 41,114.52.

Annual maintenance cost was estimated as 2% of the total CAPEX following Mahmoud et al. (2021). The annual OPEX was calculated as the sum of annual chemical, energy, maintenance and labour costs using Eq. (13).

$$OPEX_{annual} = C_{c,annual} + C_{e,annual} + C_{m,annual} + C_{l,annual} \quad (13)$$

where $C_{c,annual}$ is the annual chemical cost, $C_{e,annual}$ is the annual energy cost, $C_{m,annual}$ is the annual maintenance cost and $C_{l,annual}$ is the annual labour cost, all expressed in USD/year.

The total treatment cost per cubic metre was calculated by combining the annualised CAPEX and annual OPEX and dividing the total annual cost by the annual treatment capacity, as shown in Eq. (14).

$$C_{treatment} = \frac{C_{CAPEX, annual} + OPEX_{annual}}{Q_{annual}}$$

14

where $C_{treatment}$ is the total treatment cost (USD/m³), $C_{CAPEX,annual}$ is the annualised CAPEX (USD/year), $OPEX_{annual}$ is the annual operational expenditure (USD/year), and Q_{annual} is the annual volume of treated wastewater (m³/year).

3 Results and Discussion

3.1 Characteristics of Synthetic Textile Wastewater

The characteristics of the untreated synthetic textile wastewater are presented in Table 2. The initial MO dye colour was 1622 ± 14.00 ADMI, which exceeded the Malaysian industrial effluent discharge limits of 100 ADMI for Standard A and 200 ADMI for Standard B under the Environmental Quality (Industrial Effluent) Regulations 2009 (Department of Environment Malaysia, 2009). This value was within the range of 352–3742 ADMI reported for real textile wastewater by Daud et al. (2023). The high colour intensity was attributed to the presence of MO dye, which contains a stable anionic mono-azo structure with an azo bond ($-N = N-$). The aromatic structure of MO dye contributes to its chemical stability and resistance to degradation, resulting in persistent colour in wastewater (Chen et al., 2024).

The initial pH of the synthetic textile wastewater ranged from 11.79 to 12.58. These values exceeded the Malaysian industrial effluent discharge limits of 6.0–9.0 for Standard A and 5.5–9.0 for Standard B. The measured pH was within the range of 6.6–13.1 reported for textile wastewater in previous studies (Aragaw & Bogale, 2023; Ayaz et al., 2025; Daud et al., 2023). The alkaline condition is commonly associated with the use of alkaline chemicals during textile processing. These initial characteristics indicate that treatment is required to reduce MO dye colour and adjust the wastewater pH before discharge.

Table 2
Characteristics of untreated synthetic textile wastewater compared with reported real textile wastewater and Malaysian industrial effluent discharge limits

Parameters	Unit	Present study (synthetic)	Reported real wastewater	Malaysian industrial effluent discharge limit		References
				A	B	
MO dye colour	ADMI	1622 ± 14.00	352–3742	100	200	Daud et al., (2023)
pH	-	11.79–12.58	6.6–13.1	6.0–9.0	5.5–9.0	Aragaw & Bogale, (2023), Ayaz et al., (2025), Daud et al., (2023)

3.2 Optimisation of the Coagulation-Adsorption Process

Figure 2 shows the effects of DCD-F resin dosage and rapid mixing speed on MO dye removal efficiency using a fixed PAC-AC-CP dosage of 250 ppm. The optimum treatment condition was obtained at 120 ppm DCD-F resin and a rapid mixing speed of 180 rpm. Under this condition, the system achieved 99% MO dye removal and reduced the colour value from 1622 ± 14.00 ADMI to 9 ± 2.02 ADMI. The final colour

value was below the Malaysian industrial effluent discharge limits of 100 ADMI for Standard A and 200 ADMI for Standard B.

The high removal efficiency indicates that the combined DCD-F resin and PAC-AC-CP treatment enhanced MO dye removal through simultaneous coagulation and adsorption. DCD-F resin and PAC contributed to charge neutralisation and particle destabilisation, while AC provided adsorption sites for residual MO dye. CP further promoted floc formation through interparticle bridging. Similar combined treatment systems have been reported to improve dye removal by promoting particle destabilisation, adsorption and floc formation (Nnaji et al., 2022).

3.2.1 Effect of DCD-F Resin Dosage

As shown in Fig. 2, MO dye removal increased with increasing DCD-F resin dosage up to 120 ppm. The highest removal efficiency was obtained at 120 ppm DCD-F resin combined with 250 ppm PAC-AC-CP composite. The improvement in MO dye removal was attributed to the increased availability of cationic sites from DCD-F resin, which promoted charge neutralisation of the negatively charged MO dye molecules. At the same time, PAC assisted particle destabilisation and floc formation, while AC provided adsorption sites for residual MO dye. CP further enhanced the formation of larger flocs through interparticle bridging.

Further increases in DCD-F resin dosage above 120 ppm resulted in a decrease in MO dye removal efficiency. This reduction was likely due to excessive cationic charge from the DCD-F resin, which may cause charge reversal and restabilisation of the destabilised particles. Similar behaviour has been reported when excessive coagulant dosage shifts the particle surface charge away from the optimum neutralisation condition, resulting in increased electrostatic repulsion and reduced aggregation (Zhou et al., 2024). Therefore, 120 ppm DCD-F resin was selected as the optimum dosage for subsequent experiments.

3.2.2 Effect of Rapid Mixing Speed

Figure 2 shows that MO dye removal increased with increasing rapid mixing speed from 120 to 180 rpm. The highest removal efficiency of 99% was achieved at 180 rpm using 120 ppm DCD-F resin and 250 ppm PAC-AC-CP composite. Lower removal efficiencies were observed at 120 and 150 rpm, indicating that higher rapid mixing improved the interaction between MO dye and the treatment agents.

The improved performance at 180 rpm was attributed to better dispersion of the treatment agents and increased particle collision during the initial coagulation stage. Higher mixing intensity promotes contact between MO dye molecules, DCD-F resin and the PAC-AC-CP composite, which supports particle destabilisation and initial floc formation. The applied mixing speed also provided sufficient shear for effective mass transfer without disrupting the formed flocs (Hanif et al., 2026). Therefore, 180 rpm was selected as the optimum rapid mixing speed for subsequent experiments.

3.3 Kinetic Evaluation of MO Dye Colour Removal

The kinetic behaviour of MO dye colour removal was evaluated using the PFO and PSO models to determine the model that best described the experimental data.

3.3.1 Modelling of PFO

Figure 3 presents the PFO kinetic plots of $\ln(R_e - R_t)$ versus contact time for DCD-F resin dosages ranging from 40 to 200 ppm with a fixed PAC-AC-CP composite dosage of 250 ppm. As shown in Table 3, the PFO model produced relatively low coefficients of determination, with R^2 values ranging from 0.47425 to 0.73149. The highest R^2 value of 0.73149 was obtained at 80 ppm, while the lowest value of 0.47425 was observed at 160 ppm. These results indicate that the PFO model did not adequately describe the MO dye colour removal kinetics.

Table 3
Pseudo-first-order kinetic parameters for MO dye removal using varying dosages of DCD-F resin integrated with 250 ppm of the PAC-AC-CP composite.

DCD-F resin dosage (ppm)	$R_{e,exp}$ (ADMI)	k_1 (min^{-1})	$R_{e,cal}$ (ADMI)	Coefficient of determination (R^2)
40	1497	0.01895	281.46	0.48552
80	1585	0.04317	235.10	0.73149
120	1611	0.05530	121.51	0.63304
160	1433	0.01525	350.72	0.47425
200	1323	0.01006	445.86	0.52661

The calculated equilibrium ($R_{e,cal}$) colour removal values also showed considerable differences from the experimental values ($R_{e,exp}$). At the optimum DCD-F resin dosage of 120 ppm, the experimental equilibrium colour removal was 1611 ADMI, whereas the PFO model predicted a value of 121.51 ADMI. Similar differences were observed across the other DCD-F resin dosages, as shown in Table 3. The combination of low R^2 values and poor agreement between the experimental and calculated equilibrium values confirms the limited suitability of the PFO model for describing the kinetic behaviour of the integrated treatment system.

The poor fit of the PFO model suggests that MO dye removal cannot be adequately represented by a single first-order kinetic process. The integrated system involves simultaneous interactions among DCD-F resin, PAC, AC and CP, including charge neutralisation, adsorption and floc formation. Therefore, further evaluation using the PSO model was conducted to determine whether it provided a better description of the experimental kinetic data.

3.3.2 Modelling of PSO

Figure 4 presents the PSO kinetic plots of (t/R_t) against contact time for DCD-F resin dosages ranging from 40 to 200 ppm with a fixed PAC-AC-CP composite dosage of 250 ppm. As shown in Table 4, the PSO model provided a good fit to the experimental data, with R^2 values ranging from 0.99947 to 0.99999. The highest R^2 value of 0.99999 was obtained at 40 and 120 ppm DCD-F resin.

Table 4

Pseudo-second-order kinetic parameters for MO dye removal using varying dosages of DCD-F resin integrated with 250 ppm of the PAC-AC-CP composite.

DCD-F resin dosage (ppm)	$R_{e,exp}$ (ADMI)	k_2 (ADMI ⁻¹ min ⁻¹)	$R_{e,cal}$ (ADMI)	Coefficient of determination (R^2)
40	1497	0.005	1503.76	0.99999
80	1585	0.002	1600.00	0.99992
120	1611	0.007	1615.51	0.99999
160	1433	0.007	1445.09	0.99963
200	1323	0.003	1340.48	0.99947

The calculated equilibrium colour removal values were also close to the experimental values. At the optimum DCD-F resin dosage of 120 ppm, the experimental equilibrium colour removal was 1611 ADMI, while the calculated value was 1615.51 ADMI. Similar agreement was observed for the other DCD-F resin dosages. The high R^2 values and close agreement between the experimental and calculated equilibrium values indicate that the PSO model described the MO dye colour removal kinetics better than the PFO model.

The better fit of the PSO model suggests that the MO dye removal rate was strongly influenced by interactions between MO dye and the treatment agents. These interactions may involve charge neutralisation, adsorption and chemical interactions within the integrated DCD-F resin and PAC-AC-CP system. Further evidence of the removal mechanism is discussed based on the FESEM, FTIR and zeta potential analyses in Section 3.4.

3.4 Characterisation and Mechanism Elucidation

3.4.1 Morphological Analysis (FESEM)

FESEM analysis was used to examine the morphology of the flocs formed under the optimised treatment conditions. As shown in Fig. 5a, the floc surface exhibited a rough and porous structure. The porous surface may provide sites for interaction with MO dye and support dye entrapment within the floc structure. Figure 5b shows that the formed flocs exhibited irregular and approximately spherical morphologies. These structures indicate the aggregation of destabilised particles during the coagulation-flocculation process. The floc shown in Fig. 5c had a diameter of approximately 196 μ m, indicating the formation of relatively large aggregates during treatment.

The observed morphology supports the combined role of coagulation and adsorption in the DCD-F resin and PAC-AC-CP treatment system. The rough and porous surface may facilitate interaction between MO dye and the treatment agents, while the irregular floc structure promotes the aggregation and entrapment of destabilised particles. The formation of larger flocs may also improve solid-liquid separation during the settling stage. Similar findings were reported by Ishak et al. (2023), where the formation of porous flocs increased the available surface for interaction with contaminants. Overall, the FESEM results demonstrate the formation of rough, porous and aggregated flocs following the treatment of MO dye wastewater.

3.4.2 Functional Group Interactions (FTIR)

FTIR analysis was conducted to identify changes in the functional groups before and after treatment with DCD-F resin and the PAC-AC-CP composite. As shown in Fig. 6, the untreated synthetic textile wastewater exhibited a broad O–H stretching band at 3392 cm^{-1} and a weaker band at approximately 2337 cm^{-1} . After treatment, the O–H band shifted from 3392 to 3261 cm^{-1} . A distinct band was also observed at 1636 cm^{-1} , which was associated with C = O- and amide-related functional groups.

The shift in the O–H band and the changes observed around the C = O region indicate interactions between MO dye and the functional groups of the treatment agents. Similar changes in O–H and C = O bands have been reported during coagulant-dye interactions (Liu et al., 2024). These spectral changes suggest the involvement of hydrogen bonding and other surface interactions during MO dye removal. Electrostatic interactions may also occur between the negatively charged sulfonate groups of MO dye and the positively charged sites of DCD-F resin and PAC.

Additional bands observed in the fingerprint region were attributed to inorganic and polymer-related functional groups associated with the treatment materials. Changes in this region after treatment further indicate interactions between MO dye and the PAC-AC-CP composite. Overall, the FTIR results support the occurrence of functional group interactions during MO dye removal and provide complementary evidence for the proposed removal mechanism.

3.4.3 Electrokinetic Properties and Charge Neutralisation

Zeta potential analysis was used to evaluate changes in the surface charge of the synthetic textile wastewater before and after treatment. As shown in Table 5, the untreated wastewater had a zeta potential of -20.6 mV , indicating that the suspended particles carried a predominantly negative surface charge. After treatment with the optimised DCD-F resin and PAC-AC-CP composite, the zeta potential shifted to $+5.62\text{ mV}$.

The shift from a negative to a slightly positive zeta potential indicates substantial charge neutralisation followed by slight charge reversal. The cationic functional groups of DCD-F resin and positively charged species from PAC reduced the electrostatic repulsion between negatively charged MO dye molecules and suspended particles. This reduction in surface charge promoted particle destabilisation and

aggregation. Similar behaviour has been reported when coagulation reduces electrostatic repulsion and promotes floc formation (Kassa et al., 2024).

The CP component further supported particle aggregation through interparticle bridging. Conductivity showed only a small change from 7.24 to 7.22 mS/cm after treatment, indicating that the treatment had a limited effect on the overall ionic content of the wastewater. Overall, the zeta potential results support charge neutralisation and interparticle bridging as important mechanisms contributing to MO dye removal.

Table 5
Zeta potential and conductivity of synthetic textile wastewater before and after treatment

Parameter	Before treatment	After treatment
Zeta potential (mV)	-20.6	+ 5.62
Conductivity (mS/cm)	7.24	7.22

3.4.4 Proposed Synergistic Mechanism

The combined results support a synergistic mechanism for MO dye removal using DCD-F resin and the PAC-AC-CP composite, as illustrated in Fig. 7. Initially, the positively charged species from DCD-F resin and PAC interacted with the negatively charged MO dye molecules. This interaction reduced electrostatic repulsion and promoted charge neutralisation and particle destabilisation. The change in zeta potential from – 20.6 to + 5.62 mV supports this mechanism.

At the same time, AC provided porous surfaces for the adsorption of residual MO dye. The rough and porous floc morphology observed by FESEM supports the availability of surfaces for MO dye interaction and entrapment. FTIR analysis further indicated changes in functional groups associated with interactions between MO dye and the treatment agents. The kinetic results also showed that the PSO model provided a better fit to the experimental data than the PFO model.

Following particle destabilisation, CP promoted interparticle bridging and assisted the formation of larger flocs. PAC also contributed to sweep flocculation through the formation of aluminium hydroxide species, which assisted the entrapment of destabilised MO dye and suspended particles (Catarino et al., 2025). These combined mechanisms resulted in the formation of dense flocs that could be separated during the settling stage. Overall, MO dye removal was attributed to the combined effects of charge neutralisation, adsorption, interparticle bridging and sweep flocculation.

3.5 Techno-Economic Performance

The techno-economic analysis was conducted to evaluate the economic feasibility of applying the optimised DCD-F resin and PAC-AC-CP treatment system at the proposed industrial scale.

3.5.1 Cost Breakdown Analysis (CAPEX and OPEX)

The techno-economic assessment included the capital expenditure and operational expenditure of the proposed treatment system. As shown in Table 6, the total initial CAPEX was estimated at USD 89,207.20. The major capital components included equalisation tank, coagulation-adsorption/flocculation unit, sedimentation tank and dual-media filtration unit. Based on a 15-year system lifetime and an annual interest rate of 6%, the annualised CAPEX was USD 9,185.11/year, corresponding to USD 0.0252/m³ of treated wastewater.

The OPEX consisted of chemical consumption, energy, labour and maintenance costs. Chemical consumption was the largest contributor to the operating cost. Based on the optimised dosages of 120 ppm DCD-F resin and 250 ppm PAC-AC-CP composite, the annual chemical cost was USD 116,398.50, equivalent to USD 0.3189/m³. Energy consumption contributed USD 29,694.03/year or USD 0.0814/m³. The estimated labour cost was USD 41,114.52/year or USD 0.1126/m³, while maintenance accounted for USD 1,784.14/year or USD 0.0049/m³. The total OPEX was therefore estimated at USD 188,991.19/year, corresponding to USD 0.5178/m³.

The combined annualised CAPEX and OPEX resulted in a total annual treatment cost of USD 198,176.30/year. At a treatment capacity of 1,000 m³/day, the estimated treatment cost was USD 0.5429/m³. This value was lower than the reported treatment costs of USD 1.37–2.16/m³ for integrated membrane processes (Vergili et al., 2012) and approximately USD 4.50/m³ for a pilot-scale treatment system using Fe/Cu nanoparticles (Mahmoud et al., 2021). This comparison indicates the potential of the proposed DCD-F resin and PAC-AC-CP treatment system for cost-effective larger-scale application.

Table 6

Techno-economic performance of the integrated DCD-F resin and PAC-AC-CP treatment system at a treatment capacity of 1,000 m³/day (USD)

Cost item	Total cost (USD)	Annual cost (USD/year)	Cost per m ³ wastewater (USD/m ³)
CAPEX			
Equalisation tank	34,216.46	3,523.04	0.0097
Coagulation-adsorption/flocculation tank and agitators	18,330.25	1,887.38	0.0052
Sedimentation tank	20,041.07	2,063.50	0.0057
Dual-media filtration unit	16,619.42	1,711.19	0.0047
Total CAPEX	89,207.20	9,185.11	0.0252
OPEX			
Energy		29,694.03	0.0814
Labour		41,114.52	0.1126
Chemicals at optimum dosage		116,398.50	0.3189
Maintenance (2% of CAPEX)		1,784.14	0.0049
Total OPEX		188,991.19	0.5178
Total treatment cost		198,176.30	0.5429

3.5.2 Industrial Scalability and Feasibility

Figure 8 presents the conceptual industrial-scale configuration of the proposed treatment system at a capacity of 1,000 m³/day. The treatment process begins with an equalisation tank to homogenise the incoming textile wastewater. DCD-F resin and the PAC-AC-CP composite are then introduced into the coagulation-adsorption/flocculation unit at the optimum dosages of 120 ppm and 250 ppm, respectively. Rapid and slow mixing promote particle destabilisation, adsorption and floc formation.

The treated wastewater subsequently enters the sedimentation tank for the separation of formed flocs. The clarified wastewater then passes through a dual-media filtration unit to remove remaining suspended particles before final discharge. Adsorption occurs simultaneously within the coagulation-adsorption/flocculation unit through the AC component of the PAC-AC-CP composite. Therefore, no separate adsorption unit is included in the proposed scale-up configuration.

The proposed treatment sequence combines the optimised laboratory conditions with the separation and filtration units required for larger-scale operation. The system achieved 99% MO dye removal with an estimated treatment cost of USD 0.5429/m³. These findings indicate the potential application of the

DCD-F resin and PAC-AC-CP treatment system for larger-scale textile wastewater treatment. Further pilot-scale validation using continuous-flow operation is recommended before full-scale implementation.

4 Conclusion

The integrated DCD-F resin and PAC-AC-CP treatment system achieved 99% MO dye removal under the optimum conditions of 120 ppm DCD-F resin, 250 ppm PAC-AC-CP composite and 180 rpm rapid mixing, reducing the colour value from 1622 ± 14.00 to 9 ± 2.02 ADMI and achieving a final colour value below the Malaysian industrial effluent discharge limits. The PSO model provided the best fit to the kinetic data, while FESEM, FTIR and zeta potential analyses supported MO dye removal through charge neutralisation, adsorption, interparticle bridging and sweep flocculation. The preliminary techno-economic analysis estimated a treatment cost of USD 0.5429/m³ at a capacity of 1,000 m³/day. These findings indicate that the proposed system has potential for effective and economically feasible textile wastewater treatment, although further pilot-scale validation is required before full-scale application.

Declarations

Author Contribution

A.B.B. contributed to the conceptualisation, methodology development, experimental investigation, data analysis, visualisation, and preparation of the original manuscript draft. R.M.S.R.M. contributed to supervision, project administration, funding acquisition, and critical revision of the manuscript. S.N.H.A. contributed to supervision, technical discussion, and manuscript review and editing. N.M. contributed to industrial collaboration, provision of materials and technical information, and review of the manuscript. D.T. contributed to technical support, validation, and manuscript review. All authors have read and approved the final version of the manuscript.

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Figures

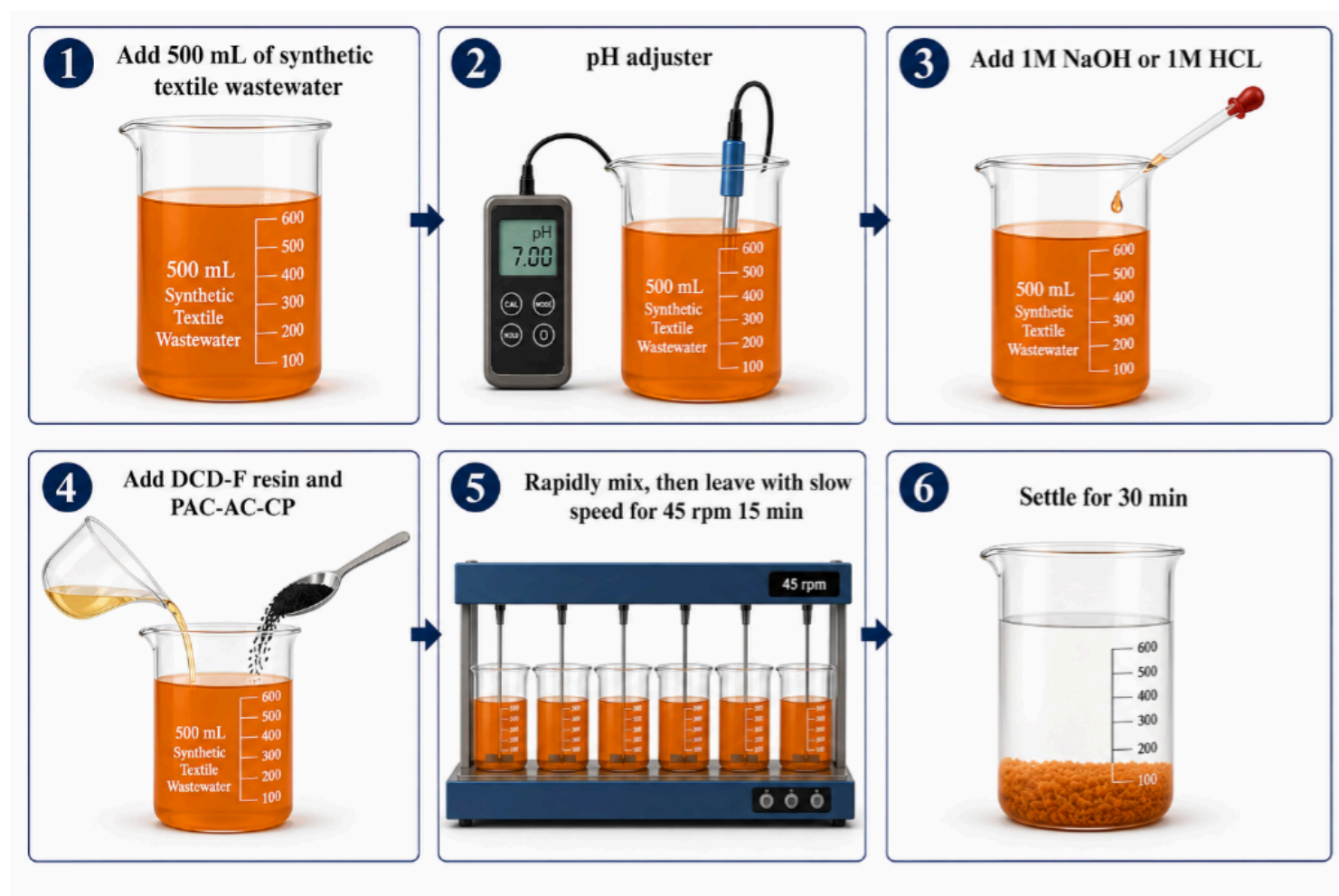


Figure 1

Jar test procedure for synthetic textile wastewater treatment using DCD-F resin and PAC-AC-CP: (1) preparation of wastewater, (2) initial pH measurement, (3) pH adjustment, (4) addition of treatment agents, (5) coagulation-flocculation and adsorption process, and (6) settling of flocs

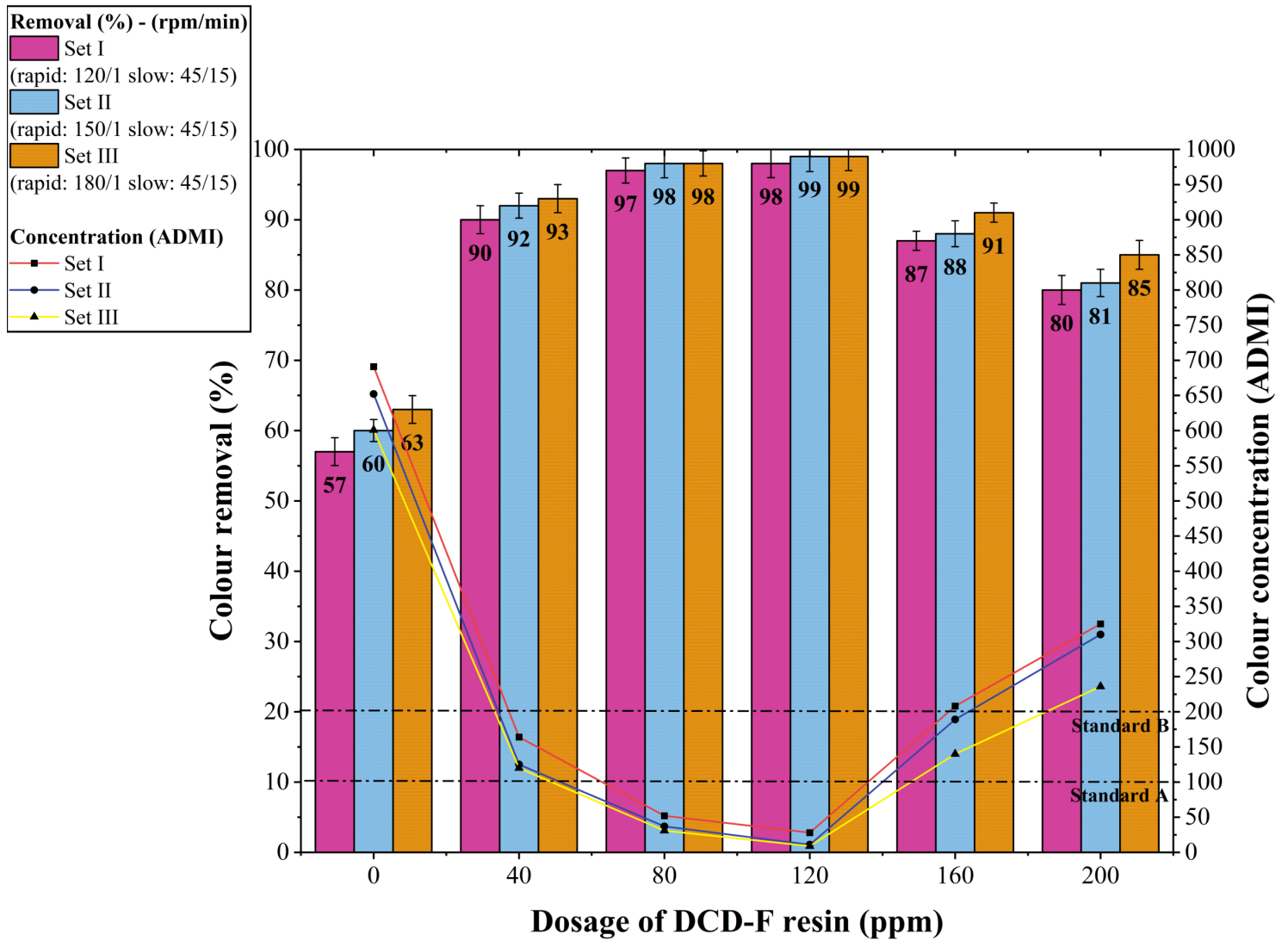


Figure 2

Effect of DCD-F resin dosage and rapid mixing speed on MO dye removal efficiency using 250 ppm PAC-AC-CP composite. Set I, Set II and Set III represent rapid mixing speeds of 120, 150 and 180 rpm, respectively. Error bars represent the standard deviation of triplicate measurements ($n = 3$). Horizontal dashed lines indicate the Malaysian industrial effluent discharge limits for Standard A and Standard B.

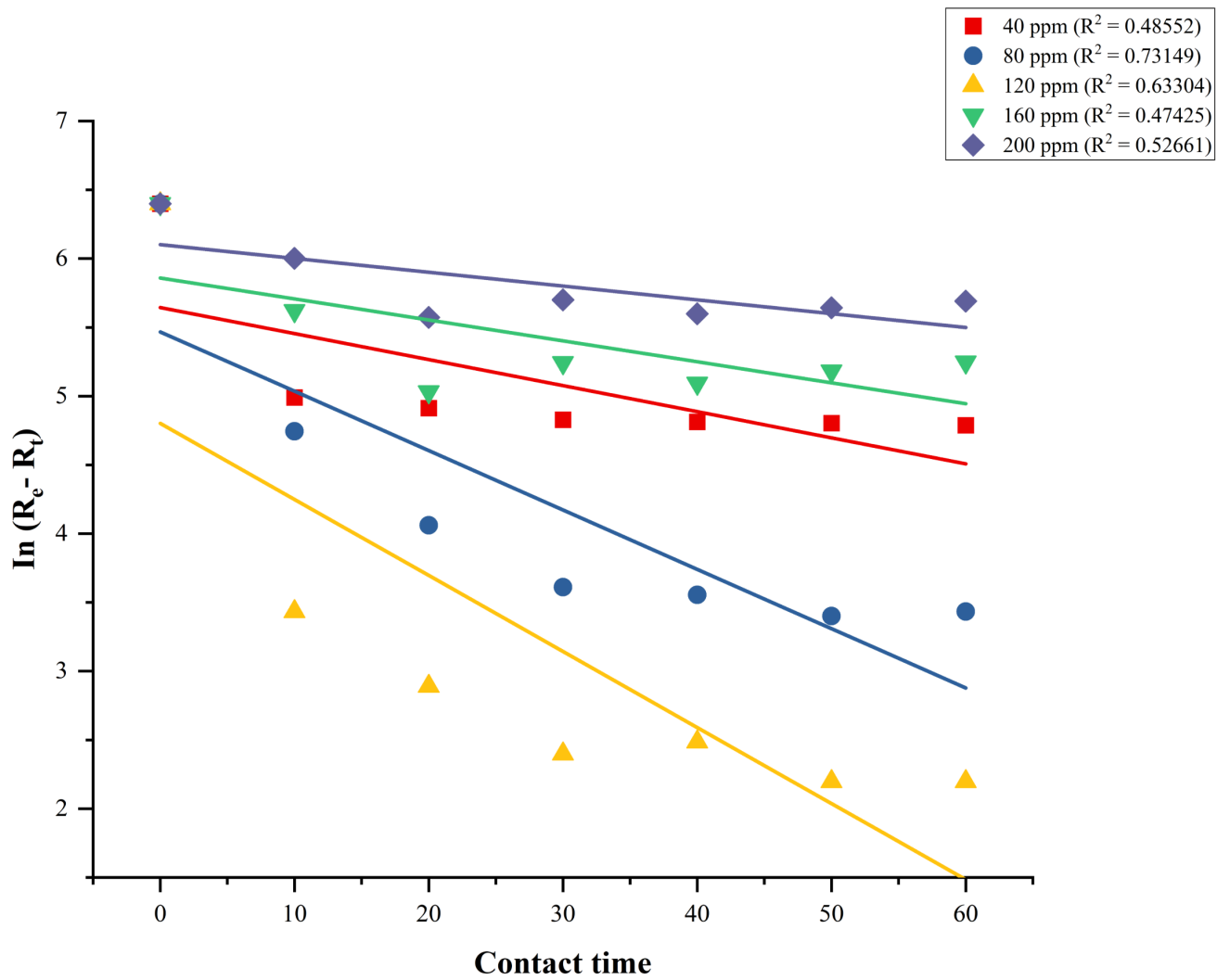


Figure 3

Pseudo-first-order kinetic model plot of $\ln(R_e - R_t)$ versus contact time using different DCD-F resin dosages and 250 ppm PAC-AC-CP composite for MO dye colour removal.

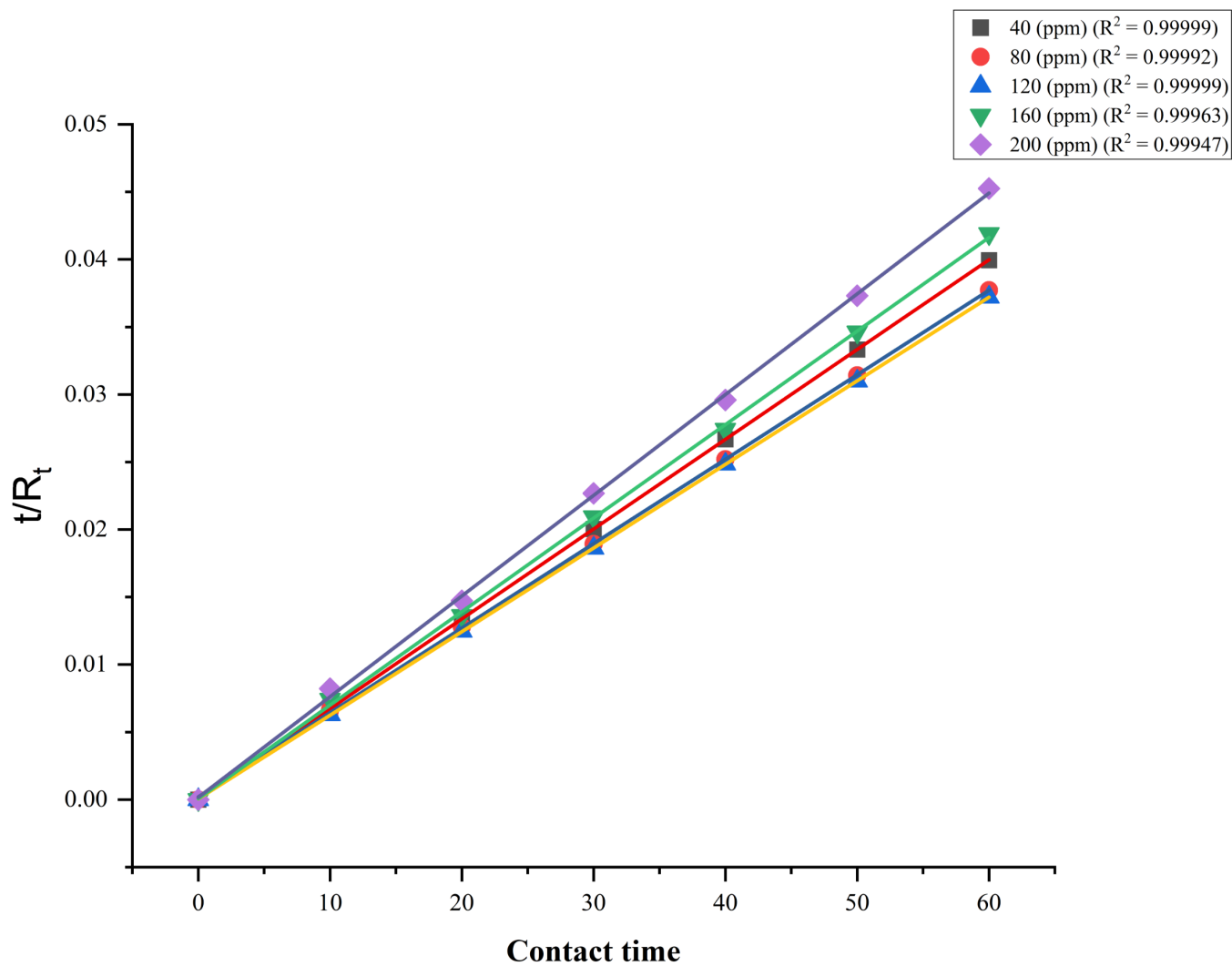


Figure 4

Pseudo-second-order kinetic model plot of t/R_t versus contact time using different DCD-F resin dosages and 250 ppm PAC-AC-CP composite for MO dye colour removal.

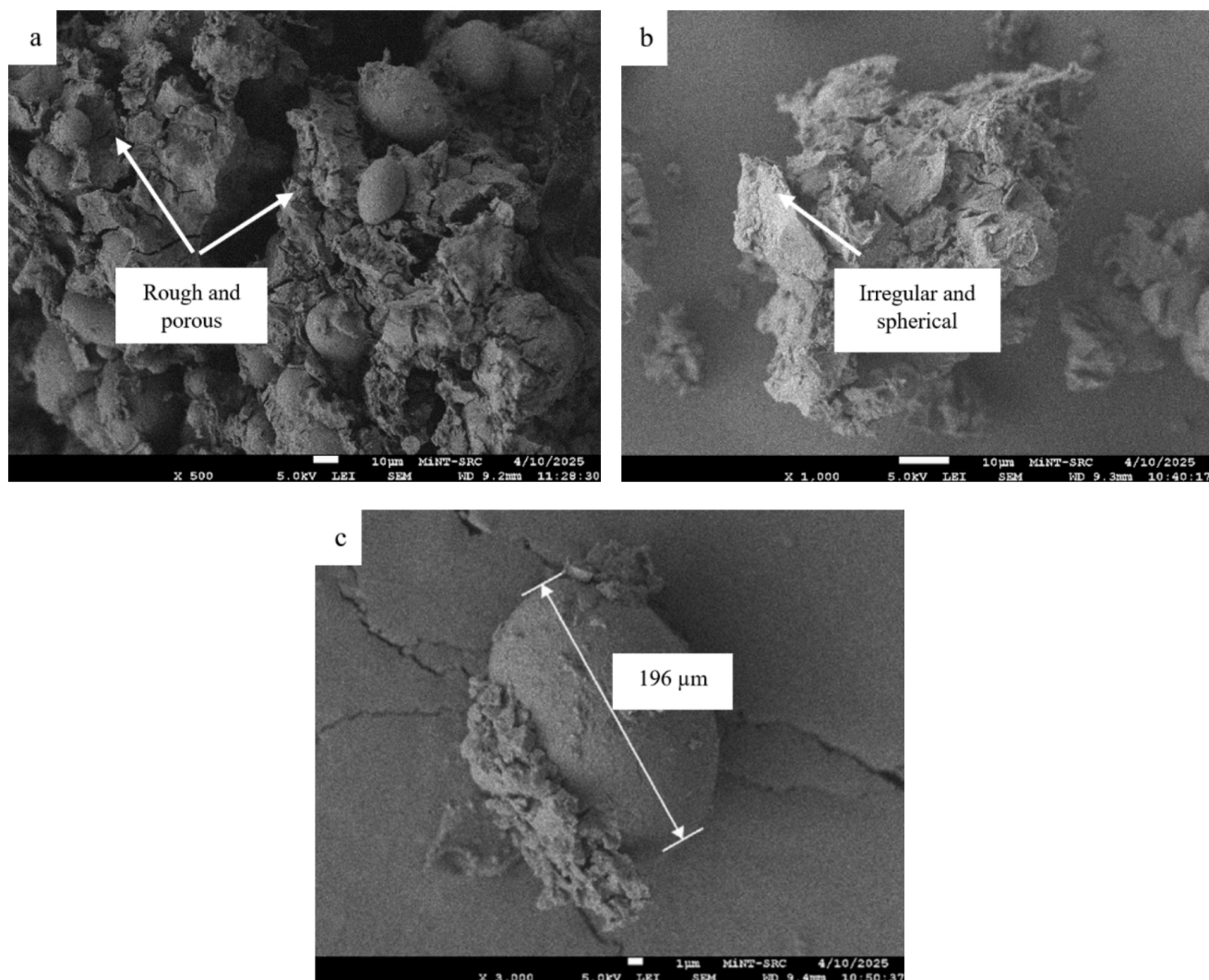


Figure 5

FESEM images of flocs formed under the optimised treatment conditions using DCD-F resin and PAC-AC-CP composite at different magnifications. (a) ×500 showing a rough and porous surface, (b) ×1000 showing irregular and approximately spherical morphology, and (c) ×3000 showing a floc diameter of approximately 196 μm. Images were captured at an accelerating voltage of 5.0 kV using a secondary electron detector.

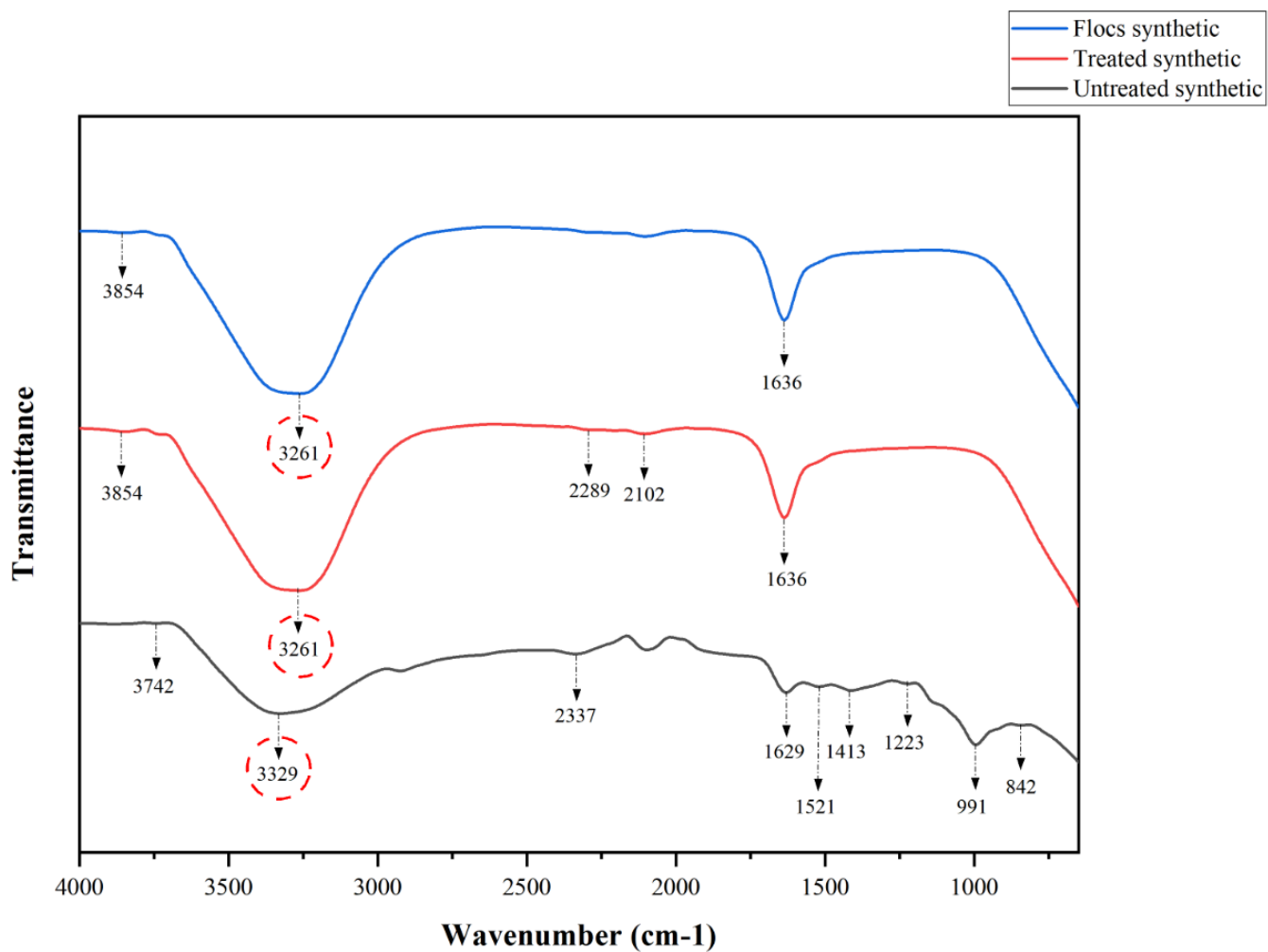


Figure 6

FTIR spectra of untreated synthetic textile wastewater, treated synthetic textile wastewater and flocs formed after treatment with DCD-F resin and PAC-AC-CP composite.

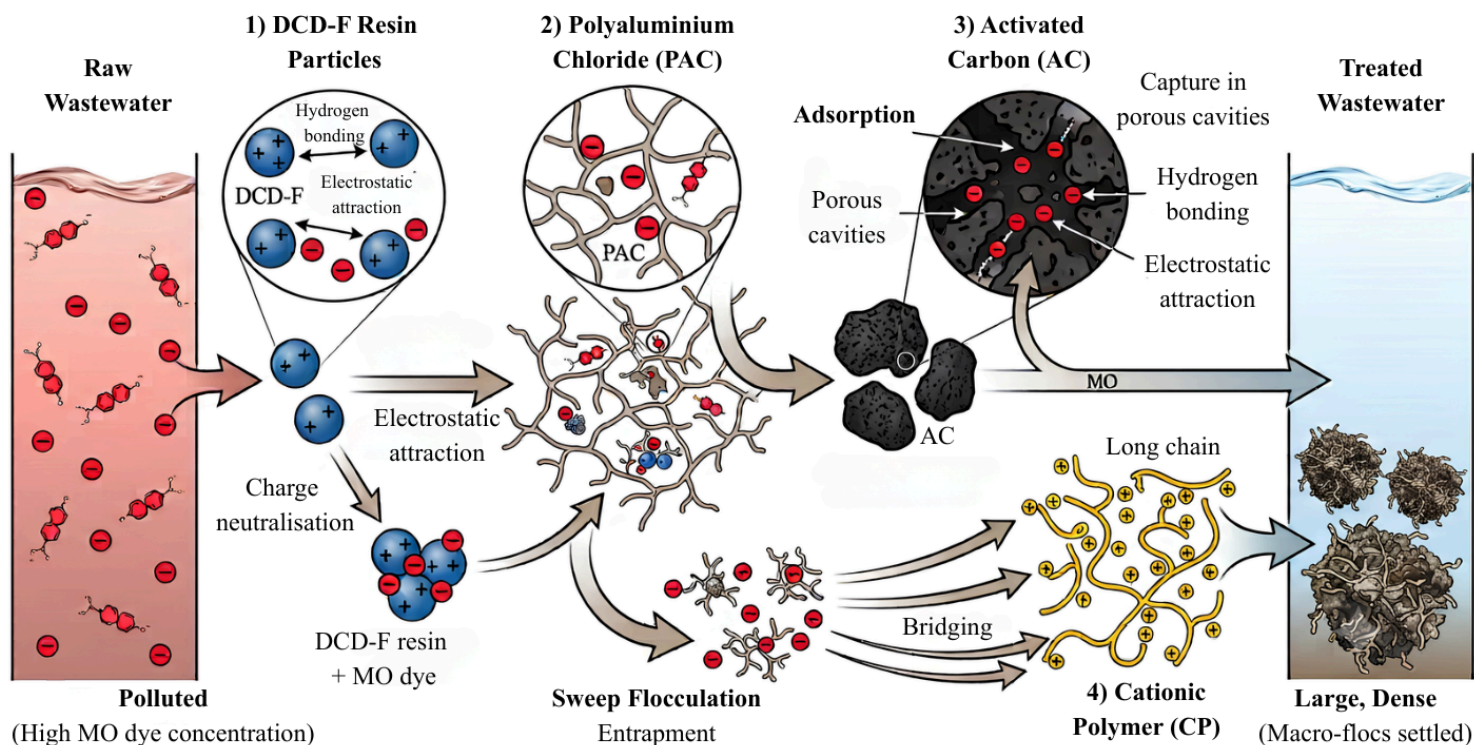


Figure 7

Proposed synergistic mechanism for MO dye removal using DCD-F resin and PAC-AC-CP composite through charge neutralisation, adsorption, interparticle bridging and sweep flocculation.

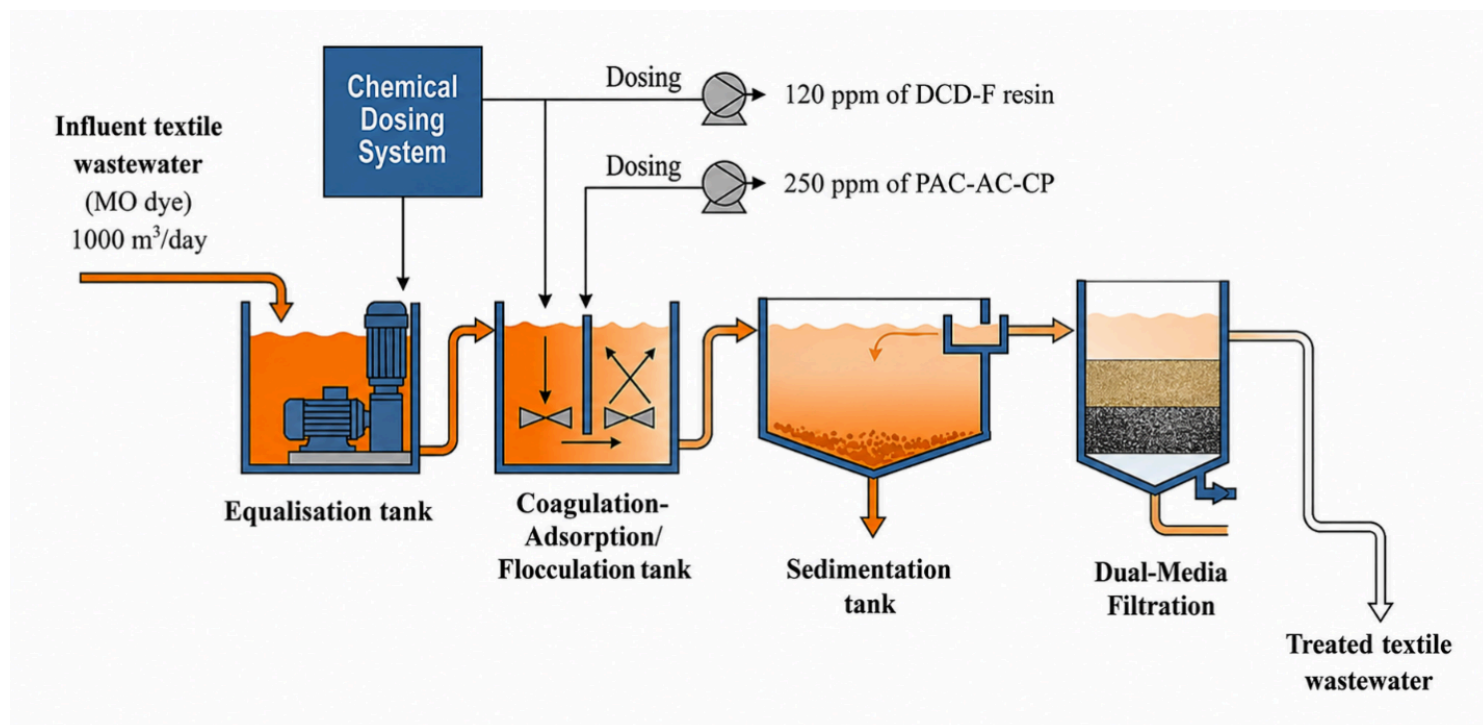


Figure 8

Conceptual industrial-scale plant layout for a 1,000 m³/day integrated coagulation-adsorption treatment system using the optimum dosages of 120 ppm DCD-F resin and 250 ppm PAC-AC-CP composite for textile wastewater treatment.