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An innovative floating cage hybrid system combining natural bentonite and *Canna indica* for advanced COD removal from textile effluent

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ABSTRACT

The manufacturing of textiles generates wastewater with a high organic content, which has a major impact on chemical oxygen demand (COD). The purpose of this study is to assess the effectiveness of a floating cage hybrid (FCH) system for decreasing COD in wastewater. FCH is a floating wetland system that incorporates both natural bentonite and *Canna indica* plants, and it is compared to a control that solely contains natural bentonite. The test employed both textile effluent and synthetic wastewater, with the latter being utilized to prevent multi-solute competition. The reactor operated on a batch system with no aeration for 27 days. At the same concentration, the natural bentonite-based system reduced COD in textile and synthetic wastewater by 25.5% and 36.7%, respectively. Meanwhile, the FCH system reduced COD in synthetic wastewater by up to 69.5%, from an initial concentration of 923 mg/L to 281 mg/L. This proves that the integration of *Canna indica* and bentonite could boost system performance through synergistic adsorption processes and biological activity. These findings demonstrate that FCH can be a viable alternative ecotechnology that uses natural materials, is low-energy, adaptable, and sustainable to improve the quality of water contaminated by the textile industry.

Keywords: adsorption, bentonite, *Canna indica*, COD, removal efficiency, textile effluent.

INTRODUCTION

The textile industry is one of the world's largest manufacturing industries, and it contributes significantly to water pollution (Souza *et al.*, 2017). Textile effluent contains hazardous, persistent, and non-biodegradable substances. High levels of dye in receiving waters can block sunlight, inhibit photosynthesis, and disrupt the balance of the aquatic ecosystem (Berradi *et al.*, 2019), while high organic matter, as measured by higher chemical oxygen demand (COD), can reduce dissolved oxygen and threaten the viability of aquatic organisms (Chaudhry *et al.*, 2022). Conventional treatment technologies, such as coagulation-flocculation, chemical oxidation, and activated sludge systems, can be ineffective, expensive, complex, and require extensive maintenance, making them difficult to implement in low-source locations (Taheriyoun *et al.*, 2020; Zazouli *et al.*, 2024). These constraints highlight the need for sustainable, low-cost, and convenient alternatives, such as adsorption and phytoremediation.

One practical option is to employ natural adsorbents such as bentonite. These clay minerals are composed of layered silicates and have an extensive surface area, a large porosity, and a significant capacity to exchange cations (Oussalah & Boukerroui, 2020; Jawad *et al.*, 2023). Its hydrophilic character allows for interaction with both organic and inorganic chemicals in wastewater, which renders it an excellent option for treating textile industry wastewater (Mohajeri *et al.*, 2019, Tebeje *et al.*, 2021; Dhar *et al.*, 2023). Research derived from textile effluent reveals that bentonite-based adsorption frequently produces lower COD reduction than synthetic matrices, owing to multi-solute rivalry and matrix effects such as a high ionic strength and active site fouling or plugging (Mohajeri *et al.*, 2019). Nonetheless, experiments using activated or modified bentonite reveal a high concentration of COD reduction from industrial textile effluents, provided pH, dosage, and exposure time are controlled, indicating that surface modification significantly increases the efficiency of real wastewater (Aichour & Zaghouane-Boudiaf, 2020). Dye contaminants, surfactants, natural organic compounds, and dissolved salts in textile effluent can all clog the pores of natural bentonite. Furthermore, bentonite's ability to filter electrostatic charges results in a significant decrease in its affinity for bulk organic charges. These matrix limits were examined utilizing adsorption-oxidation and hybrid adsorption-polishing procedures (Rizzi *et al.*, 2020).

Ecotechnology-based wastewater treatment approaches, particularly phytoremediation, are also emerging as green options. *Canna indica* is highly adaptable to a variety of environmental conditions, particularly wetlands and flooded places. This plant efficiently bioaccumulates nutrients, heavy metals, and organic substances (Ghezali *et al.*, 2022). In a floating treatment wetland (FTW), root systems hang freely in the water column, enhancing interaction with contaminants even in the absence of soil. FTWs planted to *Canna indica* decrease nitrogen by 76-92%, phosphate by 80%, and more than 80% of heavy metals such as lead (Pb) and copper (Cu) from household and small-scale industrial effluents (Wei *et al.*, 2020; Arivukkarasu & Sathyanathan, 2024). Because of the high concentration of complex organic debris and dyes in textile effluent, ecotechnology testing using the same approach frequently gives inconsistent results. Several studies show COD removal efficiency ranging from 40 to 65%, depending on the type of pollutant, retention time, and hydraulic loading rate (Rahmadyanti & Audina, 2020).

These constraints emphasize the need to improve FTW performance for reducing complex organic compounds in textile wastewater. Natural bentonite integration into aquatic macrophyte rhizospheres is both compatible and stable. This is a consequence of its large surface area and cation exchange capability. Furthermore, it stabilizes pH, promotes an aerobic environment for the root system, immobilizes detrimental ions, and its porous and layered structure facilitates microbes-plant interaction (Wang *et al.*, 2018; Salimizadeh *et al.*, 2020). Although bentonite shows promise for COD adsorption, matrix interference and multi-solute competition reduce its efficacy in actual effluents. To reduce these impacts, bentonite must be systematically evaluated in well-monitored synthetic conditions. Furthermore, even though simultaneous adsorption and phytoremediation in a single, low-energy system is possible, the incorporation of bentonite into floating modules with *Canna indica* has not received enough research attention.

Based on these considerations, this study introduced an innovative floating cage hybrid (FCH) that applies floating treatment wetland principles while redesigning the module into a cage-integrated, bentonite-packed unit to optimize root–water contact and sorbent–flow interaction; the system was then evaluated to: (1) quantify the COD reduction efficiency and analyze the adsorption kinetics of natural bentonite in real textile wastewater; (2) compare COD reduction performance between real and synthetic effluents to test the competitive-adsorption hypothesis; and (3) evaluate the FCH system using synthetic wastewater to determine the improvement in COD removal efficiency compared with bentonite alone.

MATERIALS AND METHODS

Materials

The bentonite was sourced from a local market in Bogor, West Java, Indonesia. The as-received powder was sieved through a 100-mesh screen to obtain a uniform particle size, and its cation exchange capacity (CEC) was 53.33 cmol/kg. Real textile effluent was collected from a local textile industry in Bandung, West Java, Indonesia, and subsequently diluted to 10%, 30%, and 50% of its original strength for adsorption tests. Although the present study primarily uses synthetic wastewater to eliminate multi-solute competition, the same textile wastewater source has been extensively characterized in our related studies (Zulti *et al*., 2025). To improve clarity, the key characteristics of the real effluent have now been summarized in Table 1. The rationale for employing synthetic wastewater in the current work is also detailed to emphasize the need for controlled, single-solute adsorption evaluation. Synthetic wastewater was prepared by dissolving 100 g of D-(+)-glucose monohydrate (Himedia GRM6549) in 1 L of demineralized water, yielding a COD of approximately 1,070 mg/L. For the FCH trials, synthetic wastewater with an initial COD of approximately 923 mg/L was used. *Canna indica* plants employed in the FCH units were three months old at the time of deployment.

Experimental design

Batch adsorption

Batch adsorption tests were conducted using native textile effluent with various initial concentrations (raw COD = 10,517 mg/L diluted to 10%, 30%, and 50%) and different contact times. Each experiment was performed with 100 mL of effluent and 20 g of natural bentonite (100-mesh) in an Erlenmeyer flask. Suspensions were agitated on a rotary shaker at 250 rpm at room temperature. Effluent pH was measured without adjustment. Contact time ranged from 0 to 240 min, and samples were collected every 30 min. At each interval, a portion of the sample was collected, the solids were immediately separated by filtration, and the supernatant COD was analyzed using a closed reflux colorimetric method (APHA 5220C) at 600 nm (APHA, 2017). For synthetic wastewater, D-(+)-glucose anhydrous (Himedia PCT0603)-based solution was prepared to match the original wastewater tested (COD concentration = 1,070 mg/L) and treated using the exact adsorbent dosage (20 g/100 mL) and mixing protocol, with a total contact time of 240 minutes. The fixed adsorbent dosage and contact time range followed the optimal values previously reported (Nabhani *et al*., 2024).

Removal efficiency (RE) and adsorption capacity (q) were computed for both real and synthetic effluent using the following formula:

$$RE = \frac{C_o - C_t}{C_o} x\ 100\% \tag{1}$$

Calculation of the adsorption capacity of natural bentonite using the following formula:

$$q = \frac{C_o - C_t}{m} x\ V \tag{2}$$

where: RE is removal efficiency (%), C_o is the initial concentration (mg/L), C_t is concentration at contact time t (mg/L), q is adsorption capacity (mg/g), m is mass of adsorbent (g), and V is volume of solution (L).

The adsorption rate is a key factor in determining the adsorption mechanism and evaluating the adsorbent's performance in batch adsorption. In this study, kinetic models, including the pseudo-first-order (PFO) and pseudo-second-order (PSO) models, were applied to fit the experimental results from effluent tests at 10% and 30% dilution. We focused on PFO and PSO because they are standard, minimally parameterized, and reliably capture physisorption-versus chemisorption-controlled uptake for dye-rich effluents. The PFO model is generally suitable for fast adsorption periods (Özmetin *et al*., 2009). PSO kinetic models typically indicate the nature of chemical

Table 1. Characterization of textile wastewater

Parameter	Unit	Textile wastewater	Threshold*
COD	mg/L	10,517	120
Dye	Pt-Co	1,577.33	Appear clear
BOD_5	mg/L	60.61	30
NO_3-N	mg/L	25.52	10
NH_3-N	mg/L	1.79	1
PO_4-P	mg/L	0.944	0.1
TSS	mg/L	390.5	30

Note: *The limit values are in accordance with the guidelines set by the Environmental Protection Agency (EPA).

adsorption. The PFO kinetic model is given as follows (Lagergren and Svenska, 1898):

$$ln(q_e - q_t) = ln \ \ q_e - k_1 t \quad (3)$$

The linear form of the PSO kinetic model is given as follows (Ho and McKay, 1999):

$$\frac{t}{q_t} = \frac{1}{k_2 {q_e}^2} + \frac{t}{q_e} \quad (4)$$

where: k_1 is the rate constant of the spurious first-order equation, k_2 is the rate constant of the spurious second-order equation, q_e is the theoretical adsorption amount at equilibrium, and q_t is the adsorption amount at time t.

Design and operation of the FCH system

The FCH system was developed by growing *Canna indica* on floating rafts and suspending a porous, basket-shaped ”frame” as a bentonite reservoir (see Figure 1). In our setup, the reactor measures 70 × 48 × 42.5 cm and contains 95 liters of wastewater, with an initial COD of approximately 600 mg/L. The floating mat supported six stems of *Canna indica* per tank, and the mesh basket (approximately 40 × 27 × 14 cm) was positioned about 14 cm below the root zone. Before startup, the plants were acclimatized for 30 days in tap water to ensure uniform root development and stable growth. Four net cloth bags, each weighing 500 g, were filled with two kilograms of natural bentonite and placed within the basket. Wastewater can initially come into contact with the bentonite layer before sinking through to the perforated input block, which runs parallel to the height of the basket (only this part is perforated). In the adsorbent zone, this design lengthens contact time and decreases short-circuiting. With the volume kept at 95 L, the system ran in batch mode without aeration. Wastewater was added on day 20 since water sampling and evaporation had reduced the capacity. The concentration of wastewater was half of its previous level.

Each of the three treatments – control (wastewater only), FCH with *Canna indica* (without bentonite), and FCH (*Canna indica* + bentonite) – had a duplicate tank for the 27-day experiment. To track changes in water quality, water samples were taken every three days. Using a water quality checker (Horiba U-50), field measurements of conductivity, temperature, dissolved oxygen (DO), and pH were made. The total COD load removed was calculated using the previously described equation. All tanks were kept in a greenhouse to reduce external variability, such as temperature fluctuations.

Reusability test of bentonite

The reusability of bentonite was evaluated by measuring COD removal efficiency after repeated adsorption–desorption cycles. Spent bentonite

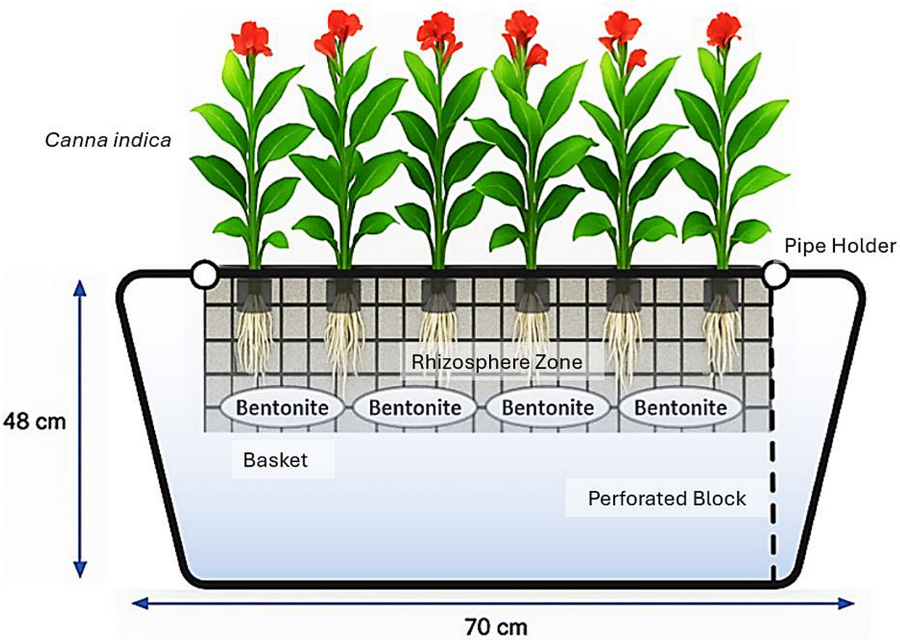

Figure 1. Design of FCH

from the FCH system was collected and regenerated by immersion in 0.1 M HCl or 0.1 M NaOH (modified from Khushbu *et al*., (2022)). After desorption, the samples were rinsed with demineralized water until neutral pH. For each regeneration type, three adsorption cycles were performed. In every cycle, 5 g of regenerated bentonite was added to 250 mL of synthetic wastewater, stirred for 1 hour, and the supernatant was analyzed for COD (APHA 5220C). Removal efficiency was calculated to assess performance across cycles.

RESULTS AND DISCUSSION

Performance of bentonite in removing COD from real textile wastewater

The textile wastewater in this study showed a very dark color (2720.67 Pt-Co) and a high organic load. The COD removal time shows distinct behaviors across dilution (Figure 2). At 10% dilution (C_o = 979 mg/L), removal efficiency rises rapidly to 27% in the first 30 minutes, then declines and recovers after 240 minutes as intraparticle diffusion contributes to additional adsorption. This pattern is consistent with systems in which control shifts from film capture to intraparticle diffusion control (Wu *et al.*, 2009). At 30% dilution (C_o = 3395 mg/L), removal efficiency increases with contact time and reaches a maximum of 35% then decreases after 120 minutes, indicating site saturation and the limit of natural bentonite in lowering COD. At 50% dilution (C_o = 4188 mg/L), removal efficiency becomes negative, meaning the measured COD exceeds the initial value, consistent with displacement of weakly bound species and the release of soluble organics under multi-solute competition. Overall, an initial COD of about 3,395 mg/L is a reasonable upper limit for an efficient batch treatment with natural bentonite in the matrix. Natural minerals remove 79–88% of COD under optimized conditions (C_0 = 440 mg/L) (Assila *et al.*, 2020), while bentonite-based hybrids obtain 93–98% elimination via catalyst ozonation-electro-flocculation or 96% with bentonite-CNT from an initial concentration of 1,150 $\pm$ 15 mg/L, demonstrating the requirement for combinations or integrated stages at higher levels (Tripathi *et al.*, 2023).

This configuration is likewise consistent with multi-solute competing on the bentonite surface.

The presence of multiple dyes and process additives can compete for the same active sites, reducing net capacity and even displacing weakly bound species, leading to an apparent increase in measured COD (Hendaoui *et al.*, 2024). The visual results in Figure 2 confirm that the increased clarity at 10%, 30%, and 50% does not always correspond to COD reduction, because chromophores can be adsorbed or oxidized more rapidly than non-chromophore organic compounds that contribute to COD. Therefore, the competition hypothesis holds at high concentrations, while at moderate loads, bentonite performance remains modest and aligns with reports on real effluents using natural or activated clays. Binary and ternary dye studies on bentonite directly demonstrate competitive displacement and decreased uptake compared to single-dye systems (Anirudhan & Ramachandran, 2015; Shirazi *et al.*, 2020),

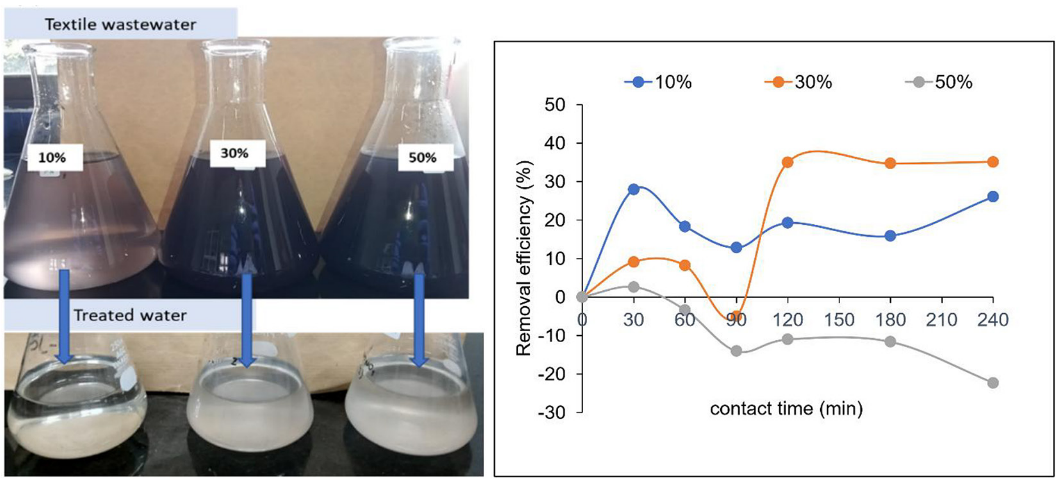

Figure 2. Visual comparison before and after treatment and removal efficiency of bentonite after 4 hours of stirring for eliminating COD from textile wastewater

consistent with our approximately 35% COD removal at moderate load and the deterioration observed at higher concentrations.

Adsorption kinetics model

Table 2 and Figure 3 indicate that COD adsorption at 10% dilution aligns better with both kinetic models than at 30%. At 10% loading, the PSO model more accurately describes the kinetics than the PFO model (R^2 0.7503 vs. 0.5525), which is typical for systems where surface reactions dominate the early stages before film-to-intraparticle diffusion takes over. At 30% loading, neither model fits the data well (PFO 0.571; PSO 0.158), suggesting multi-step, non-ideal transport mechanisms that standard PFO/PSO models cannot capture. The stronger fit of PSO at 10% indicates a greater role of chemisorption compared to physisorption under moderate loading, consistent with reports of PSO dominance and site-specific interactions in bentonite matrices (Jamil *et al.*, 2023). The sharp decline in PSO fit and the very small k_2 at 30% support the idea of competitive adsorption in multi-solute mixtures, where dyes and auxiliaries compete for overlapping sites and displace weakly bound species, thereby reducing overall capacity and affecting simple kinetic models (Adeyi *et al.*, 2019). Literature on higher-performance variants confirms this, showing that modified or composite sorbents maintain PSO kinetics at higher loadings due to additional interaction domains, whereas unmodified clays lose fit as concentration and matrix complexity increase (Santos *et al.*, 2025).

FTIR analysis

The FTIR spectra (Figure 4) show clear, assignment-consistent changes in bentonite after contact with real textile effluent at 10% dilution. These interpretations follow established FTIR fingerprints of bentonite (O–H at 3400 and 1630 cm^{-1}; Si–O stretches near 1000–1040 cm^{-1}; Al–OH bending around 913–920 cm^{-1}) (Benhouria *et al.*, 2023; Oussalah *et al.*, 2019a). The broad band near 3392 cm^{-1} (O–H stretching of structural –OH and interlayer/bound water) slightly shifts and weakens, indicating hydrogen bonding between clay hydroxyls and polar organics in the liquor. The band around 1629 cm^{-1} also shifts, showing that adsorbed water is partly replaced or rearranged by these organics at the clay surface. Simultaneously, the Si–O stretching region near 995 cm^{-1} shifts to about 1007 cm^{-1} with a significant increase in intensity, indicating disruption of the tetrahedral sheet and occlusion by organic matter, as previously reported (Bahranowski *et al.*, 2021). The peak near 915 cm^{-1} (Al–OH bending) decreases, indicating interaction at edge hydroxyl sites where organics can attach (Jawad *et al.*, 2023).

Taken together, these shifts demonstrate that organics contributing to COD really bind to bentonite, not just remain in the water phase. The most significant changes occur at surface –OH and Si–O zones, suggesting specific sites are preferred and may be competed over when many different organics are present. This aligns with the kinetic and performance behavior observed on the same samples.

Comparison of COD removal in real versus synthetic wastewater

Synthetic-wastewater tests were conducted at the same initial concentration as the 10% dilution because the adsorption capacity at 10% (q = 0.96 mg g^{-1}) was lower than at 30% (q = 3.32 mg g^{-1}). This indicated the adsorbent was far from saturation and many bentonite sites remained available, whereas 30% already showed

Table 2. Kinetic model parameters of color and COD adsorption on bentonite

Kinetic model		Initial concentration	
		10%	30%
Pseudo-first-order	*qe* exp. (mg/g)	1.344	5.794
	k_1 (1/min)	0.0084	0.037
	R^2	0.5525	0.5709
Pseudo-second-order	*qe* exp. (mg/g)	1.344	5.794
	k_2 (1/min)	0.0268	0.00011
	R^2	0.7503	0.1583

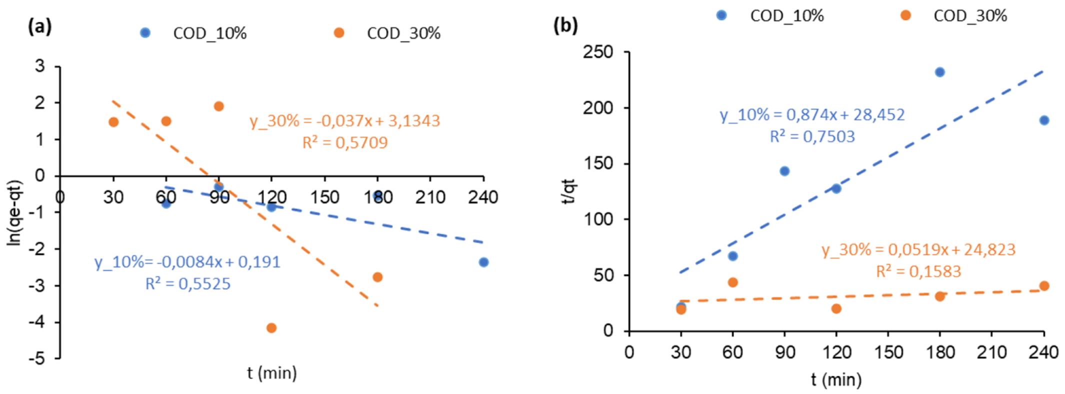

Figure 3. Kinetic plots of COD adsorption at 10% and 30% dilution

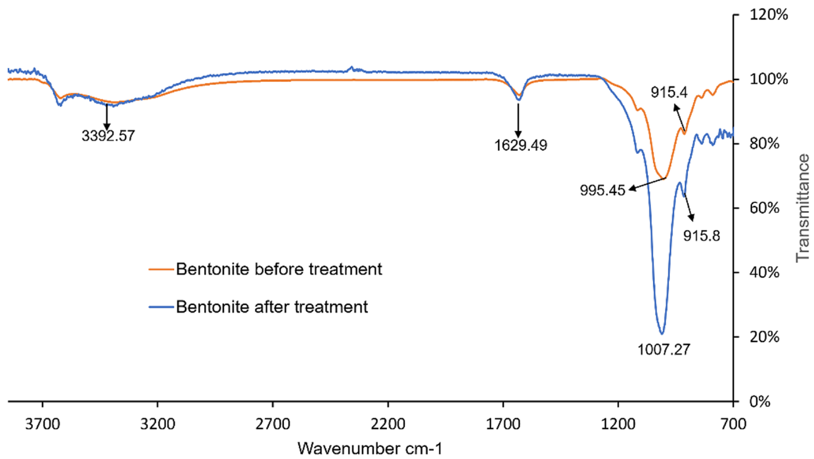

Figure 4. FTIR spectra of natural bentonite before and after use to reduce pollutants in textile wastewater

signs of site saturation (Figure 2). The 100-mesh size shortened the external boundary layer, so early uptake was rapid, whereas the moderate CEC (53.33 cmol/kg) limited the total number of high-affinity sites. This combination was consistent with PSO dominance at 10% and diffusion-limited behavior at 30%. Kinetic fitting at 10% showed acceptable agreement with both the PFO and PSO models, yielding interpretable rate parameters under minimal multi-solute interference. The 10% setting offers a practical balance between stable performance, adequate model fit, and reduced competitive effects, making it the most appropriate basis for investigating the intrinsic mechanisms and actual capacity using controlled synthetic wastewater.

Batch comparisons (see Figure 5) show that bentonite performs much better in synthetic effluent than in real effluent. The likely reason is multi-solute competition and matrix effects, which reduce net uptake. Within four hours, our simulated test eliminated 36.7% of COD, while real wastewater removed only 25.5%. This finding is consistent with prior research showing that salts, surfactants, and co-pollutants interact with clay adsorption in real textile effluent (Lafi *et al.*, 2018). Advantages such as selective enhancements or pairing steps are critical over practical deployment: bentonite-based catalyst ozonation and electro-flocculation improved the removal efficiency on real denim effluent, whereas membrane hybrids such as UF/ED improved COD retention about single-step baselines (Jamil *et al.*, 2023). Scale-up also favors continuous contact to reduce diffusion limitations and re-release; a pilot fixed-bed using zeolite–bentonite on real textile wastewater showed vigorous polishing with longer residence times, supporting our plan to move beyond batch processes (Zulti *et al.*, 2025). From a design perspective, natural bentonite is suitable for pre- or mid-treatment at moderate loads, but upstream oxidation and downstream polishing are recommended to meet discharge standards. Pilot studies should therefore combine bentonite

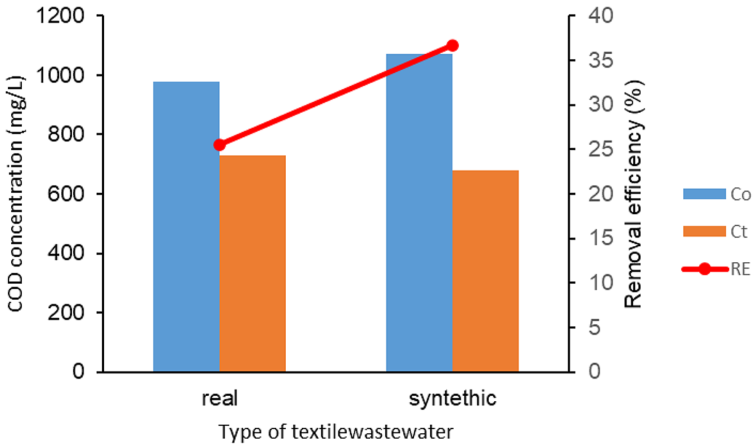

Figure 5. Comparison of COD removal efficiency between real and synthetic effluent

adsorption with phytoremediation within a sustainable FCH setup to measure the additional COD removal achieved beyond adsorption alone.

COD removal in the FCH system

Overview and trend

The FCH improved COD removal in synthetic wastewater from 36.7% with bentonite alone to 69.5% with Bentonite–Canna. As shown in Figure 6, the Bentonite–Canna unit performed best, increasing rapidly and continuing to improve after day 14, reaching a maximum of 69.5% at day 20 (final concentration is 281.33 mg/L). The control rose quickly to 48% by day 2 and then stabilized near 37%, confirming natural attenuation through settling and indigenous biofilms without aeration. The Canna unit increased after a short dip, reaching a late peak of 64.5% at day 27, consistent with the lag time needed for rhizosphere biofilms to mature in floating wetlands. The pattern suggests initial adsorption by bentonite, followed by biological polishing on roots and attached biofilms. Similar floating wetland studies using *Canna indica* report 25–50% COD removal for domestic influents, which is lower than our peak on synthetic water, highlighting the added value of the combined system.

Figure 7 shows that pH and temperature stayed within environmental ranges (pH 6.0–7.0; 26–28 °C). DO decreased in planted units to less than 1 mg/L under unaerated operation, while Control recovered to 4.8 mg/L by day 18. Despite the low DO, COD removal in Bentonite–Canna continued to increase after day 14, consistent with facultative/anaerobic biodegradation and filtration/ adsorption pathways known to sustain COD reduction in wetlands without forced aerations. Over the same period, conductivity and TDS increased (to >450 µS/cm and 240 mg/L), indicating ion release and exchange from raw bentonite; the measured CEC (53.33 cmol/kg) supports such ion exchange (e.g., Na^+/Ca^{2+} release), which explains the EC/TDS rise despite ongoing COD decline. Laboratory observations show raw Na-bentonite can elevate conductivity via Na^+ release, whereas acid-activated clays tend to lower it.

Throughout the experiment, pH and temperature were allowed to fluctuate naturally, and the FCH system maintained stable performance under these conditions. However, the study did not include controlled manipulation of pH, temperature, or organic load to evaluate the system under extreme scenarios. Controlled stress-testing will be needed for industrial-scale applications.

Role of integration and improvement levers

The FCH increased COD removal from 65.0% to 69.5%, resulting in a modest 4.5% gain that clarifies function rather than scale. Bentonite rapidly absorbs organics, allowing *Canna indica* to biodegrade at a lower rate in low oxygen conditions. Conductivity and TDS increased to indicate that ion exchange occurs from bentonite, which increases ionic strength and may impair electrostatic adsorption later on. This trade-off clarifies why progress was observed but not significant, despite ongoing COD reduction. It highlights the distinct roles of bentonite and plants, with bentonite providing rapid collection and pH stability, and plants gradually processing leftover organic

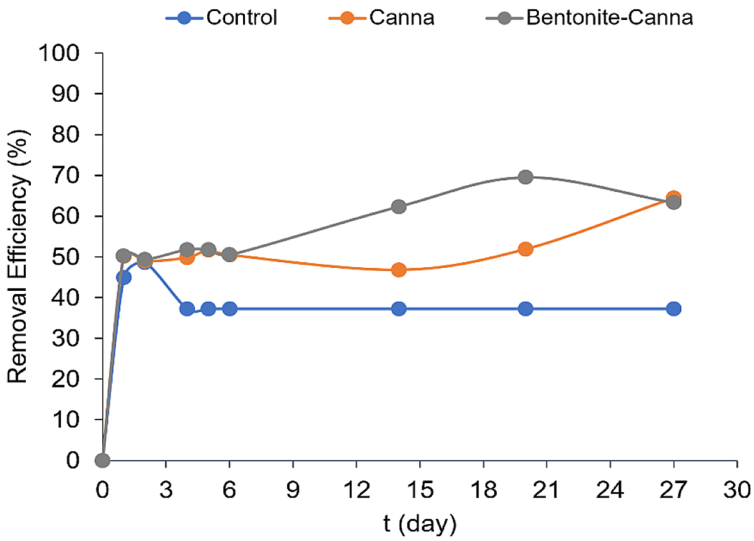

Figure 6. Performance of FCH for COD removal over time

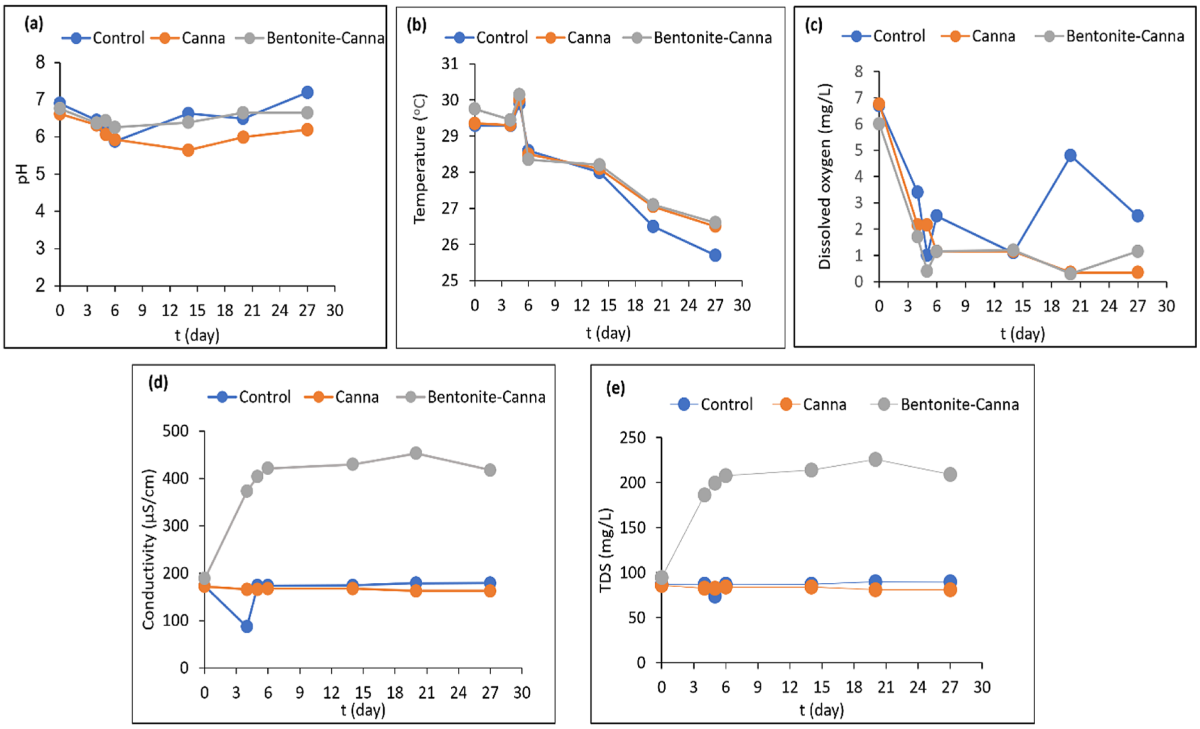

Figure 7. Water quality indices in the FCH include pH (a), temperature (b), dissolved oxygen (c), conductivity (d), and total dissolved solids (e)

matter in the root zone. Insufficient dissolved oxygen availability resulted in the dominance of facultative metabolism. This shows that contact time and biofilm formation have a greater impact on COD removal efficiency than oxygen input. The observed increases in EC and TDS must be regulated with bentonite dosage and granulation to regulate buffering and site availability. These findings demonstrate the FCH as a viable module that outperforms a plant-only system while indicating great potential for adaptation.

Reusability performance of regenerated bentonite

Figure 8 shows the COD removal efficiency of bentonite regenerated using 0.1 M HCl and 0.1 M NaOH across three adsorption cycles. NaOH regeneration produced the highest initial recovery (73% in Cycle 1), indicating that strong

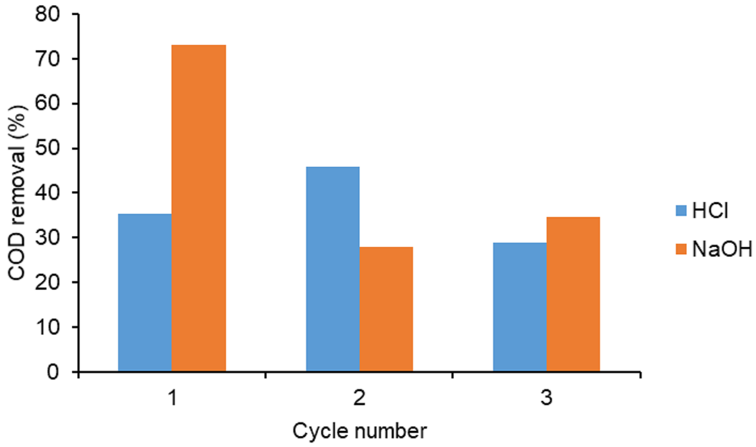

Figure 8. COD removal efficiency of bentonite regenerated with 0.1 M HCl and 0.1 M NaOH across three adsorption cycles

alkaline conditions effectively desorb retained organics and reopen partially blocked pores (Khushbu1 *et al*., 2022; Oussalah *et al*., 2019). However, the sharp drop in Cycle 2 and only partial stabilization in Cycle 3 suggest that repeated alkaline exposure may alter or weaken some active sites. In contrast, HCl-regenerated bentonite showed a more moderate but stable pattern (35% → 46% → 29%), implying that acidic desorption is less aggressive and better preserves bentonite's structural integrity over multiple cycles.

The reusability test demonstrates that bentonite gradually loses adsorption capacity with repeated use, but does not lose its functionality entirely. Compared with the maximum COD removal achieved by the full FCH system (69.5%), NaOH-regenerated bentonite still maintained 34% removal in Cycle 3–approximately half of the integrated system's peak performance. This indicates that despite efficiency decline, bentonite retains a functionally meaningful adsorption capacity for up to three regeneration cycles.

Limitations and future work

This study successfully demonstrated the potential of the FCH for COD removal under controlled conditions. However, several limitations should be acknowledged. BOD_5 was not measured in this study because the primary objective was to evaluate the COD removal performance of the FCH system, given that COD represented the dominant pollutant in the wastewater. Although biodegradability indicators such as the COD/BOD_5 ratio could provide additional insights, these were beyond the scope of the present study. Future research will incorporate BOD_5 and related biodegradability metrics to obtain a more comprehensive assessment of system performance. Future work will also examine FCH performance under intentionally varied pH, temperature, organic loading, and optimized adsorbent dosage and plant density to simulate a wider range of industrial conditions.

CONCLUSIONS

Natural bentonite reduced COD, but its performance was bound in complex matrices. The best outcome appeared at 30% dilution, with 35% removal efficiency (from 3,395 mg/L to 2,200.62 mg/L). At 50% dilution, the removal became negative. Real–synthetic contrasts revealed multi-solute competition: 36.7% removal in 4 h for the synthetic matrix versus 25% for the real effluent at equal initial strength. The FCH that integrates bentonite with *Canna indica* delivered superior outcomes, peaking at 69.5% (from 923 mg/L to 281 mg/L), and outperformed plant-only and control units. Reusability testing further showed that bentonite retains a meaningful portion of its adsorption capacity for up to three cycles, with regenerated material still achieving about 34% COD removal in the third cycle. Bentonite remains useful yet constrained; competition explains the gap between matrices, and the FCH offers a credible nature-based route to enhance COD reduction.

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