



# Performance of Pilot-scale Constructed Wetlands for Treating Paper Mill Effluent

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## Abstract

Wastewater discharged from the paper industry generates substantial volumes, ranging between 75 and 225 m<sup>3</sup> per ton of product, containing high levels of organic content (COD 480-4450 mg/L), chloride (80-980 mg/L), and a variety of volatile fatty acids (approx. 950 mg/L), cellulose (approx. 1,200 mg/L). The objective of this study was to investigate the efficiency and reaction coefficients of the free water surface flow constructed wetlands (FWS CWs) for removing pollutants such as color, dissolved solids, suspended solids, chemical oxygen demand (COD), biochemical oxygen demand (BOD<sub>5</sub>), and nitrogen (TKN). Three pilot-scale units were established, each containing sand as the media and planted with (1) Narrowleaf cattail (*Typha angustifolia* L.), (2) Loop-root mangrove (*Rhizophora mucronata* Lam.), and (3) Unplanted control. Upon evaluating the system's performance, it was observed that the FWS CWs effectively reduced contaminants in the factory effluent, particularly color, COD and TKN. The color removal efficiency ranged from 31.15-93.55% (56.86±18.31), 17.86-89.25% (54.30±21.39%), and 27.87-91.40% (58.11±18.84%) for control, cattail, and mangrove unit, respectively. Regarding COD removal, the efficiencies ranged from 31.15-93.55% (56.86±18.31), 17.86-89.25% (54.30±21.39%), and 27.87-91.40% (58.11±18.84%) for control, cattail, and mangrove unit, respectively. Both COD and color removal efficiency presented no statistically significant differences observed among the three units ( $P > 0.05$ ). The removal efficiency of TKN was 40.00 and 85.74%, 20.00 and 85.71%, and 80.00% and 85.71% for control, cattail, and mangrove unit, respectively. The reaction kinetics of color removal appear to align with both Plug Flow Reactor (PFR) and Continuous Stirred Tank Reactor (CSTR) models. Rate constants for color removal were calculated for the control and mangrove units, as no color removal was observed in the cattail unit. For the mangrove unit, the first-order reaction rate constants were 0.021 d<sup>-1</sup> for the PFR model and 0.023 d<sup>-1</sup> for the CSTR model, while for the control unit, they were 0.030 d<sup>-1</sup> for the PFR model and 0.035 d<sup>-1</sup> for the CSTR model. COD reduction can be described by the CSTR model, with first-order reaction rate constants of 0.140 d<sup>-1</sup> for the control unit, 0.131 d<sup>-1</sup> for the cattail unit, and 0.143 d<sup>-1</sup> for the mangrove unit.

**Keywords :** free water surface flow, paper mill wastewater, Narrowleaf cattail (*Typha angustifolia* L.), Loop-root mangrove (*Rhizophora mucronata* Lam.)

## Introduction

The paper industry plays a significant role in global economy by providing essential products for various sectors. However, the paper production often generates substantial volumes of wastewater, between 75 and 225 m<sup>3</sup> per ton of product [1], with effluent containing high levels of chemical oxygen demand (COD) (480-4450 mg/L), chloride (80-980 mg/L), total dissolved solids (395-2500 mg/L), volatile fatty acids (approx.950 mg/L), and cellulose (approx.1,200 mg/L). Adsorbable organic halides (AOX) are also commonly presented [2]. Effluent of the paper mills can pose serious environmental challenges if it is not properly treated before discharge.

Constructed wetlands have emerged as a promising eco-friendly solution for tertiary treatment of wastewater from various sources, including the effluent generated by pulp and paper mills. These engineered systems mimic the natural processes occurring in wetlands, utilizing the combined mechanisms of physical, chemical, and biological processes to remove pollutants from wastewater [3]. Numerous studies have demonstrated the effectiveness of constructed wetlands in treating pulp and paper mill effluent. For example, the research conducted by Abira et al. [4] evaluated the performance of a pilot-scale constructed wetland system in removing phenols from pre-treated pulp and paper mill wastewater. The study reported significant reductions in phenols by 60% at 5-day hydraulic retention time (HRT) and 77% at 3-day hydraulic retention time (HRT) on average. Similarly, investigations by Rani et al. [5] documented the successful treatment of pulp and paper mill effluent using a small wetland system planted with cattail and canna. The study revealed high removal efficiencies for color, TS, BOD and COD, highlighting the potential of constructed wetlands for addressing the specific challenges associated with pulp and paper mill wastewater.

The study paper factory, located in central Thailand, specializes in producing corrugated paper from recycled materials. It discharges 30,000 m<sup>3</sup>/day of effluent with total suspended solids (TSS) of 11.0 to 127.0 mg/L, chemical oxygen demand (COD) of 90.0 to 352.0 mg/L, biochemical oxygen demand (BOD<sub>5</sub>) of 7.0 to 33.0 mg/L, and ammonia nitrogen (NH<sub>3</sub>-N)

of 70.4 to 22.8 mg/L. To improve the water quality of the effluent before discharging it into the nearby river, a low-cost and sustainable constructed wetland system was proposed as a tertiary wastewater treatment solution.

This paper aims to explore the application of constructed wetlands for the treatment of paper mill effluent. It will delve into the principles behind constructed wetlands, their design considerations, and the mechanisms by which they effectively remove contaminants from wastewater. The significance of this study lies in addressing the persistent need for sustainable and efficient wastewater treatment methods in the pulp and paper industry. By evaluating the feasibility and effectiveness of constructed wetlands, this paper seeks to contribute to the development of environmentally sound practices for mitigating the environmental impact of pulp and paper production.

## Methodology

### Paper mill wastewater characteristics

The paper factory, located in the central Thailand, specializes in producing corrugated paper derived from recycled materials. For the study, the paper mill effluent (PME) was sourced from the secondary clarifier of the factory's wastewater treatment plant. Table 1 presents the wastewater characteristics observed over a one-year period (2023); indicating TSS ranged from 11.0 to 127.0 mg/L (41.30±24.3), COD ranged from 90.0 to 352.0 mg/L (187.73±48.6), BOD<sub>5</sub> ranged from 7.0 to 33.0 mg/L (15.31±4.7) and NH<sub>3</sub>-N ranged from 0.4 to 22.8 mg/L (10.1±3.3). Most of the time, effluent complied with Thai standards.

### Pilot scale unit setup

The pilot study was conducted within the area of Suranaree University of Technology, where a small-scale constructed wetland system was set up using a fiberglass tank with the size of 2.30 m (length) x 0.80 m (width) x 0.55 m (height). The tank's full capacity was 1,012 liters, with a total working volume of 552 liters and a void volume of 300 liters. A layer of sand, less than 2.00 mm in size and 0.20 meters thick, was placed within the tank. The pilot-scale constructed wetland tank was equipped with a piping system comprising an inlet pipe (Ø 1/2 inch), an outlet pipe (Ø 1/2 inch), and a sampling

**Table 1** Wastewater characteristic of paper mill effluent

Parameter	Unit	Ranges	Average $\pm$ SD	Industrial Eff. standard <sup>1/</sup>
pH	-	7.1-8.1	7.1 $\pm$ 0.8	-
TSS	mg/L	11.0-127.0	41.30 $\pm$ 24.3	40
Turbidity	NTU	5.3-92.1	21.77 $\pm$ 18.9	-
COD	mg/L	90.0-352.0	187.73 $\pm$ 48.6	270
BOD <sub>5</sub>	mg/L	7.0-33.0	15.31 $\pm$ 4.7	30
NH <sub>3</sub> -N	mg/L	0.4-22.8	10.1 $\pm$ 3.3	10 (TKN)
Phosphorus	mg/L	0.2-12.3	1.3 $\pm$ 0.7	-

<sup>1/</sup>Ministerial Notifications on the requirements on the characteristic of discharge wastewater from pulp and paper industry, 2018. (B.E. 2562) issued by Department of Industrial Works

<sup>2/</sup>Data obtained from paper factory (2023)

pipe (Ø 4 inch). Three sampling pipes were positioned eventually within a perforated plastic basket filled with 3/8-inch crushed stone to facilitate water passage. Figure 1 illustrates the setup of the FWS CWs system and the positioning of the sampling pipe.

**Cultivated-plant species**

Narrowleaf cattail (*Typha angustifolia* L.) had exhibited promising efficacy in the removal of contaminants from wastewater in Subsurface Flow Constructed Wetlands (SFCW) [6, 7]. Additionally, the Loop-root mangrove (*Rhizophora mucronata* Lam.), a macrophyte commonly found in the vicinity of the factory and demonstrated to be effective in treating wastewater in the Laem Phak Bia development and environment research project under the Royal Projects demonstration site, was selected for inclusion in this study. In the pilot-scale units, Narrowleaf cattail shoots were carefully separated from the main rhizome, retaining only the supportive rhizome and root portions to promote initial growth. Two to three shoots were then planted directly into the media at a depth of 0.20 m, spaced 0.2 m apart (9 plants m<sup>-2</sup>). For the loop-root mangrove, nursery-raised seedlings approximately 30 cm tall were planted at a depth of 0.20 m and spaced 0.12 m apart (9 plants m<sup>-2</sup>) [8]. Before the application of the PME load, the plants underwent a nurturing period of 4 weeks in a nursery setting.

**Pilot scale experiment operation**

The experimental units were operated as continuous plug flow reactors. Initially, they were filled with clean water for a period of four weeks after planting, followed by a gradual increase in the supply of paper mill effluent (PME) over the subsequent four weeks. PME was collected weekly from the factory. The hydraulic retention time was set at 7 days, with the flow rate of PME into the experimental units controlled by inlet and outlet valves. Samples were collected from 5 points: the inlet, 3 sampling pipes, and the outlet of the system. These samples were then analyzed for pH, EC, TDS, color, TSS, BOD<sub>5</sub>, and COD, following the methods outlined in APHA 2022.

The water quality was monitored at weekly intervals over a period of 2 months. The performance of pollutant removal in the pilot-scale constructed wetland was determined using the percentage removal equation (1):

$$\text{Percentage of removal, \%} = \frac{C_{in} - C_{out}}{C_{in}} \times 100 \quad (1)$$

where  $C_{in}$  and  $C_{out}$  are the concentration of influent and effluent of the constructed wetland cell.

Two kinetic models, incorporating first-order biological degradation kinetics with plug-flow (PFR) and Continuous Stirred Tank Reactor (CSTR) flow patterns, were employed to calculate the constant rate for color and COD removal [9, 10].

The PFR first order reaction coefficient was determined using equation (2):

$$C_t = C_0 e^{-kt} \quad (2)$$

where  $C_t$  and  $C_0$  are the concentration at time  $t$  and influent of the constructed wetland cell.

The CSTR first order reaction coefficient was determined using equation (3):

$$C_t = \frac{C_0}{1+kt} \quad (3)$$

where  $C_t$  and  $C_0$  are the concentration at time  $t$  and influent of the constructed wetland cell.

### Statistical analysis

Statistical analysis was performed by the SPSS statistics 17.0 for windows software package program network Licensed in Suranaree University of Technology. Data was calculated by mean, minimum, maximum and standard deviation for a result. Significance of different was determined with  $t$ -test (Significant at level of 0.05). Pearson correlation coefficient (significant at level of 0.05) was used to determine correlation.

## Results and Discussion

### Performance of treatment system

The pilot-scale of FWS CW units was planted with Loop-root mangrove (*Rhizophora mucronata* Lam.) and Narrowleaf cattail (*Typha angustifolia* L.) and supplied with the effluent of the paper factory. Additionally, the control system without plants was conducted for comparison, aiming to assess the potential of the units as tertiary treatment system and to serve as a control. Data collection was conducted at 8-13 different times to ensure the comprehensive data coverage. The results are depicted in Figure 3 and summarized in Table 2.

**1) pH:** The influent pH ranged from 7.60 to 8.16. After treatment, the pH increased slightly, with average values of  $8.29 \pm 0.16$  for the control unit,  $8.28 \pm 0.12$  for the cattail unit and  $8.23 \pm 0.16$  for the mangrove unit. The pH of the treated PME across all three units showed no statistically significant differences ( $P > 0.05$ ).

**2) EC:** The EC of the PME ranged from 2.89-3.43 mS/cm. After treatment, all three units exhibited a slight reduction in EC compared to the influent values. The average EC values

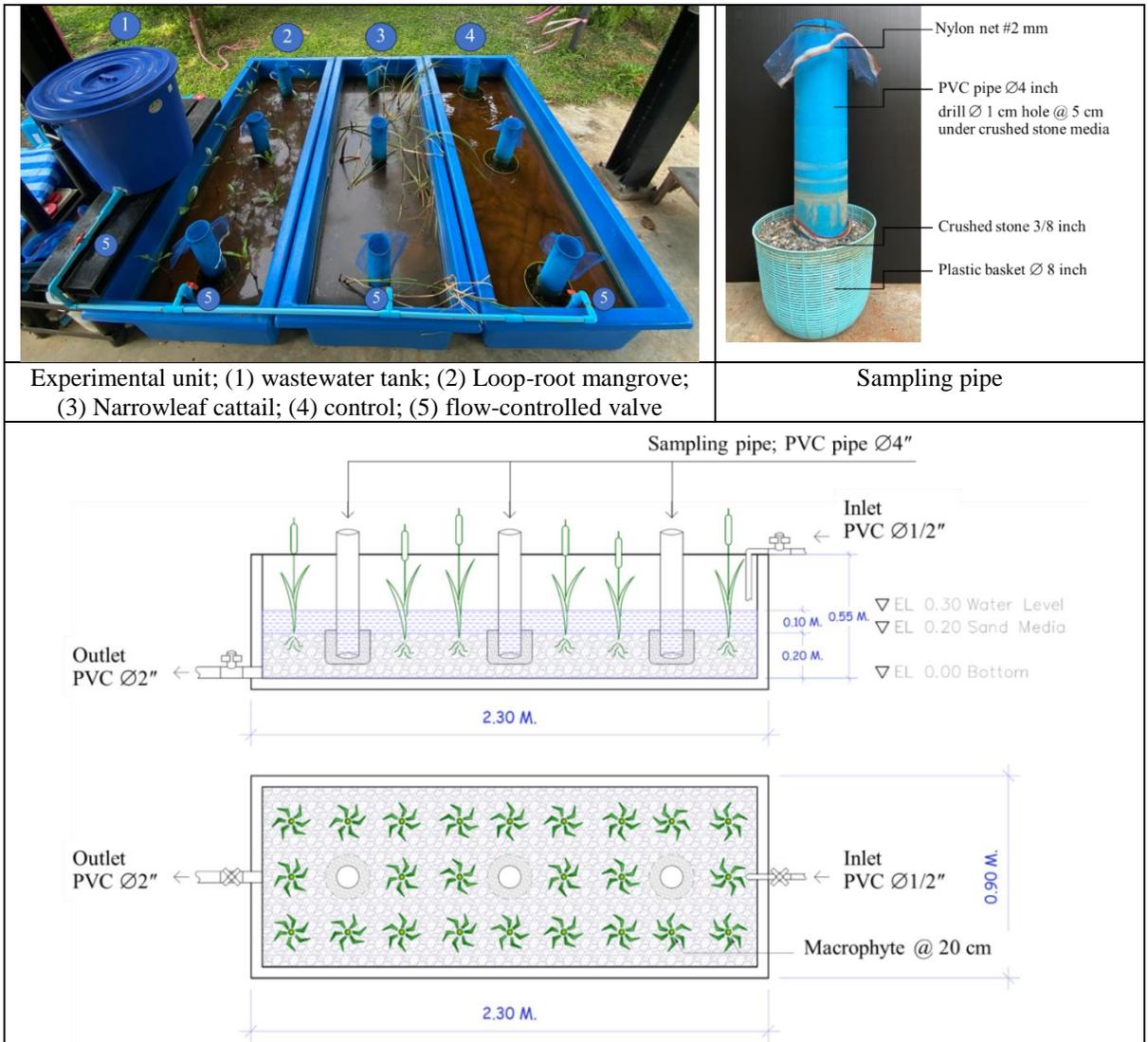
were  $2.95 \pm 0.11$  mS/cm for the control unit,  $3.01 \pm 0.32$  mS/cm for the cattail unit, and  $2.91 \pm 0.10$  mS/cm for the mangrove unit. No statistically significant differences were observed among the three units ( $P > 0.05$ ).

**3) Total dissolved solids (TDS):** All three FWS CWs units exhibited some reduction of TDS compared to its original state. Prior to treatment, the TDS levels contained in the paper mill effluent (PME) ranged from 1,422 to 1,688 mg/L. After treatment, the reduction of TDS levels ranged from 0.00-14.22% ( $6.00 \pm 5.39\%$ ), 0.00-11.49% ( $6.67 \pm 5.19\%$ ) and 0.00-16.29% ( $7.32 \pm 6.31\%$ ) for control, cattail, and mangrove units, respectively. When comparing the TDS levels of the treated PME from all three units, no statistically significant differences were observed ( $P > 0.05$ ). Moreover, TDS reduction of such 3 units was relatively low as not exceeding 16.29%. The TDS levels contained in PME primarily consist of highly soluble inorganic pollutants, such as  $\text{Cl}^-$  ( $459.05 \pm 83.75$  mg/L), which are resistant to biodegradation. Consequently, these pollutants cannot be easily reduced through chemical precipitation, ion exchange, or plant absorption in constructed wetlands, resulting in low overall removal efficiency.

**4) Color:** All three FWS CWs units exhibited a reduction of color in PME. Prior to treatment, color levels contained in PME ranged from 118.20 to 174.71 ADMI. After treatment, the reduction of color levels ranged from 0.00-29.39% ( $16.47 \pm 9.86\%$ ), 0.00-10.69% ( $3.56 \pm 3.90\%$ ), and 1.74-22.26% ( $14.06 \pm 6.95\%$ ) for control, cattail, and mangrove units, respectively. The color contained in the paper and pulp manufacturing process is generated by lignin compounded in the plants used as raw material for paper production. It exhibits a three-dimensional network structure of polymers, composed of units of phenylpropane. In its normal state, lignin is a complex polymer embedded within the cell structure of wood tissue and is insoluble in typical solvents. In the papermaking process, lignin is separated out during the pulp bleaching process [11]. Generally, soil infiltration systems have good color removal capabilities because of the slow flow of wastewater through the medium within the treatment system, allowing lignin to be filtered out by the medium, such as rocks, gravel, sand, and plant roots. Additionally, mechanisms

such as sedimentation and settling to the bottom, as well as decomposition within the system, also contribute to color removal [12, 13]. When comparing the color removal efficiency of the treated paper mill effluent across all three units, the control unit and the unit planted with mangrove demonstrated better treatment performance than the unit planted with cattail ( $P > 0.05$ ). However, no significant difference in color removal was observed between the control unit and the unit planted with mangrove ( $P > 0.05$ ). This finding suggests that the presence of

mangrove in the FWS CWs does not substantially influence color reduction during the experimental period. Soil filtration appears to play a dominant role in color removal. This might be due to the constraint faced by any phytoremediation process that requires longer time for full contamination. Similar results were reported by Md Yusoff et al. [14], where no significant difference in color removal was observed between an SSF system planted with *S. grossus* and a control.



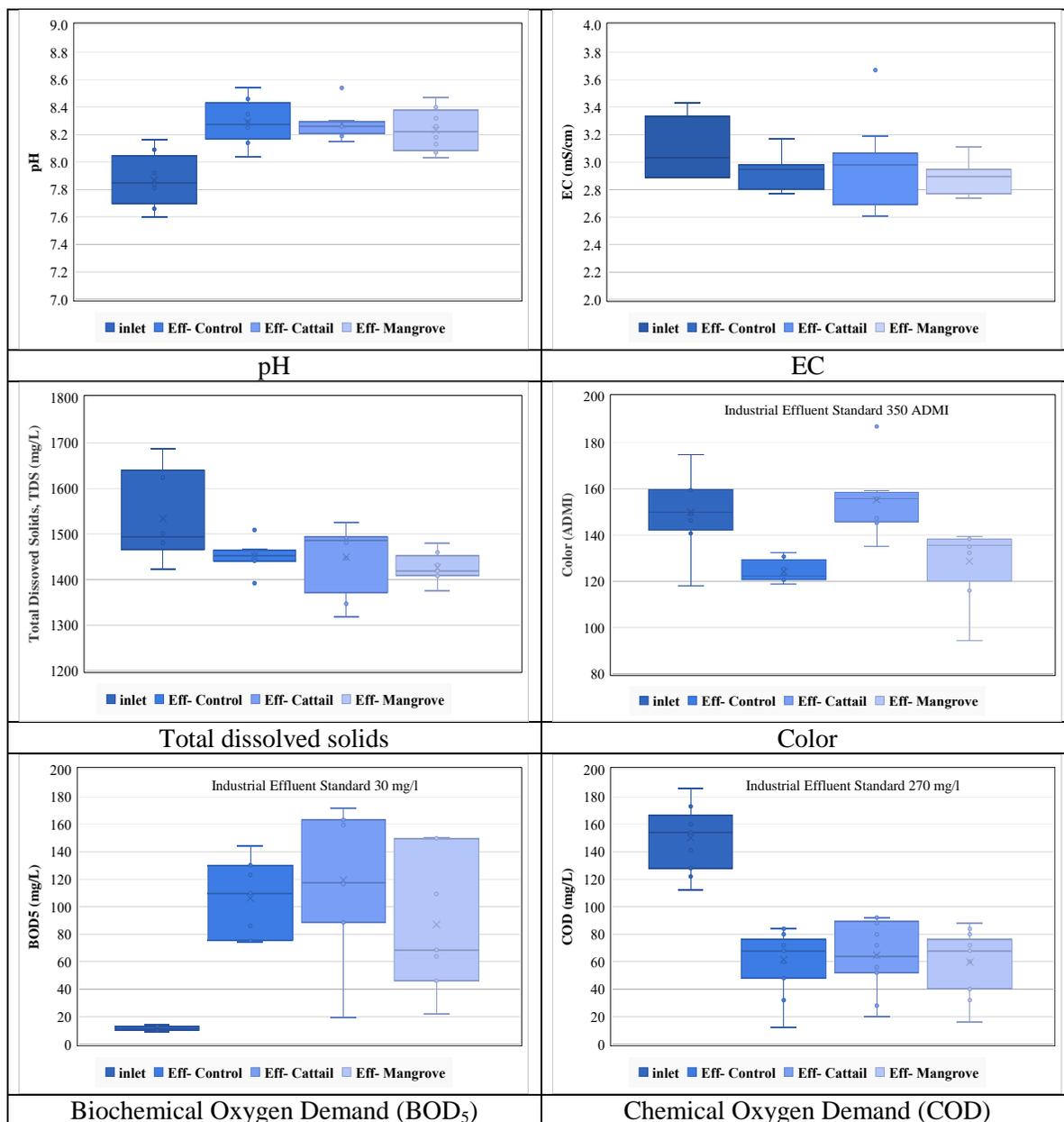
**Figure 1** The pilot-scale of FWS constructed wetland



**Figure 2** Photo of plants in the pilot-scale constructed wetland at the beginning and at the end of the experiments

**Table 2** Experimental results and removals (in %) of pH, EC, TDS, Color, BOD<sub>5</sub> and COD

Parameter		Inlet	Eff-Control	Eff-cattail	Eff-mangrove
pH (mg/L)	Ranges	7.60-8.16	8.04-8.54	8.15-8.54	8.03-8.47
	Avg. $\pm$ SD	7.87 $\pm$ 0.19	8.29 $\pm$ 0.16	8.28 $\pm$ 0.12	8.23 $\pm$ 0.16
EC (mS/cm)	Ranges	2.89-3.43	2.77-3.17	2.61-3.67	2.74-3.11
	Avg. $\pm$ SD	3.12 $\pm$ 0.20	2.95 $\pm$ 0.11	3.01 $\pm$ 0.32	2.91 $\pm$ 0.10
TDS (mg/L)	Ranges	1,422-1,688	1,392-1,509	1,318-1,526	1,376-1,480
	Avg. $\pm$ SD	1,533.67 $\pm$ 100.56	1,451.63 $\pm$ 32.50	1,449.38 $\pm$ 75.66	1,425.88 $\pm$ 32.07
	% removal	-	0.00-14.22	0.00-11.49	0.00-16.29
	% removal	-	6.00 $\pm$ 5.39	6.67 $\pm$ 5.19	7.32 $\pm$ 6.31
Color (ADMI)	Ranges	118.2-174.7	119.0-132.3	145.3-187.0	94.3-139.3
	Avg. $\pm$ SD	151.2 $\pm$ 17.4	123.2 $\pm$ 4.5	158.1 $\pm$ 13.7	127.3 $\pm$ 16.5
	% removal	-	0.00-29.39	0.00-10.69	1.74-22.26
	% removal	-	16.47 $\pm$ 9.86	3.56 $\pm$ 3.90	14.06 $\pm$ 6.95
BOD <sub>5</sub> (mg/L)	Ranges	9.0-14.0	74.5-143.9	19.3-171.7	22.0-149.9
	Avg. $\pm$ SD	11.0 $\pm$ 9.0	106.1 $\pm$ 27.9	119.4 $\pm$ 53.6	87.0 $\pm$ 50.3
	% removal	-	-	-	-
	% removal	-	-	-	-
COD (mg/L)	Ranges	112.0-186.0	12.0-84.0	20.0-92.0	16.00-88.00
	Avg. $\pm$ SD	150.08 $\pm$ 22.29	61.54 $\pm$ 21.33	64.77 $\pm$ 23.77	59.69 $\pm$ 21.63
	% removal	-	31.15-93.55	17.86-89.25	27.87-91.40
	% removal	-	56.86 $\pm$ 18.31	54.30 $\pm$ 21.39	58.11 $\pm$ 18.84
NH <sub>3</sub> -N (mg/L)	Ranges	0.7-1.0			
TKN (mg/L)	Ranges	5-10	1.0-4.0	1.0-3.0	1.0-1.0
Nitrate (mg/L)	Ranges	1.0-9.0			
	% removal	-	40-85.74	20.00-85.71	80.00-85.71



**Figure 3** Graphical representation of pH, EC, TDS, Color, BOD<sub>5</sub> and COD at the inlet and outlet of FWS CWs units

**5) Biochemical Oxygen Demand (BOD<sub>5</sub>):**

The effluent of all three experimental units exhibited an increase in BOD<sub>5</sub> compared to its original state. Initially, the BOD<sub>5</sub> level contained in PME ranged from 9.0 to 14.0 mg/L. After treatment, the BOD<sub>5</sub> levels varied, ranging from 74.5 to 143.9 mg/L (106.15±27.89) for the control unit, 19.3 to 171.7 mg/L (119.43±53.61) for the cattail unit, and 22.0 to 149.9 mg/L (87.04±50.26) for the mangrove unit. However,

upon the treatment with FWS CWs, it was observed that the BOD<sub>5</sub> levels contained in the effluent from all three units exceeded the standard limit of 20 mg/L set by the National Standard (Ministerial Notifications on the requirements on the characteristic of discharge wastewater from pulp and paper industry, 2018. (B.E. 2562)). It is worth noting that the paper mill effluent (PME) used in the experiment had a relatively low BOD<sub>5</sub> concentration of

9.0-14.0 mg/L. Upon passing through the experimental units placing with plants, the plant leaves undergone with microbial decomposition, which is a primary process in reducing organic matter. This decomposition occurred under both aerobic and anaerobic conditions, resulting in an increase in BOD<sub>5</sub> levels. Additionally, the wastewater contained nitrogen derived from the decomposition of proteins in paper tissue (ammonia nitrogen levels contained in PME ranged from 0.4 to 22.8 mg/L), as well as phosphorus (phosphorus levels in PME ranged from 0.2 to 12.3 mg/L). Nitrogen serves as a nutrient that stimulates algal and plant growth, increasing nutrient loads in the system and ultimately causing a rise in BOD<sub>5</sub>.

#### 6) Chemical Oxygen Demand (COD):

The effluent of all three experimental units exhibited a decrease in COD compared to its original state. Prior to treatment, the COD levels contained in PME ranged from 112.0 to 186.0 mg/L. After treatment, the reduction in COD ranged from 31.15-93.55% ( $56.86 \pm 18.31$ ), 17.86-89.25% ( $54.30 \pm 21.39\%$ ), and 27.87-91.40% ( $58.11 \pm 18.84\%$ ) for control, cattail, and mangrove unit, respectively. After treatment, the COD levels varied, ranging from 12 to 84 mg/L for the control unit, 20 to 92 mg/L for the cattail unit, and 16 to 88 mg/L for the mangrove unit. No statistically significant differences in COD levels were observed among the treated effluents from the three units ( $P > 0.05$ ). The BOD<sub>5</sub>/COD ratio, an indicator of organic matter biodegradability, revealed a low ratio for the PME before treatment ( $15.31:187.73 = 0.081$ ), indicating low biodegradability. Post-treatment, the BOD<sub>5</sub>/COD ratios increased to  $1.45 \pm 0.54$ ,  $1.56 \pm 1.03$ , and  $1.24 \pm 0.76$  for the control, cattail, and mangrove units, respectively. A BOD<sub>5</sub>/COD ratio greater than 1 suggests the activity of an aerobic nitrifying bacteria, which consume oxygen to convert ammonia (NH<sub>3</sub>-N) into nitrate (NO<sub>3</sub>-N). High ammonia levels contained in wastewater can increase oxygen demand, resulting in a higher BOD relative to COD [15].

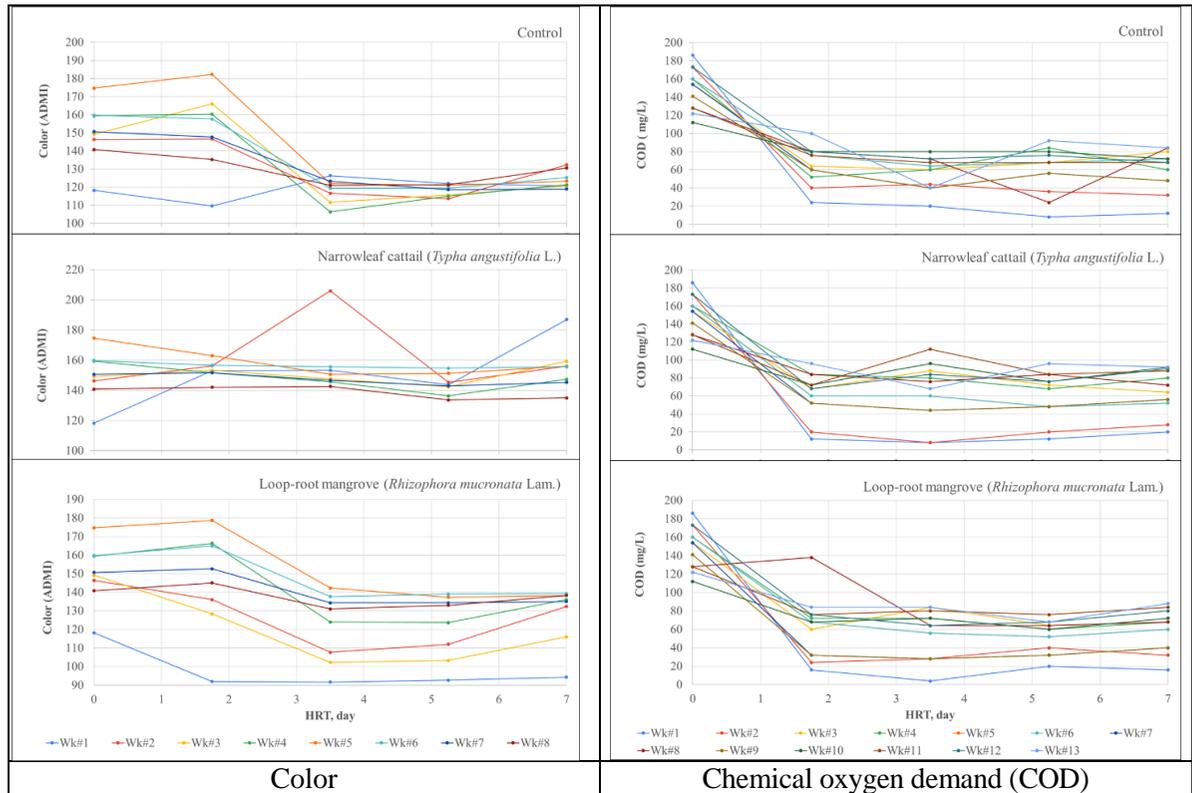
7) **Nitrogen:** Nitrogen transformation and treatment efficiency were assessed through two sampling events. The results showed that the system effectively removed nitrogen. The treatment efficiency of TKN was 40 and

85.74% in the control unit, 20 and 85.71% in the cattail unit, and 80% and 85.71% in the mangrove unit. Nitrogen in the effluent was primarily in the form of NH<sub>3</sub>-N, with concentrations ranging from 0.4 to 22.8 mg/L (Table 1). Upon entering the constructed wetland unit, NH<sub>3</sub>-N was transformed into nitrite (NO<sub>2</sub>-N) and subsequently nitrate (NO<sub>3</sub>-N), with nitrate concentrations of 9.0 mg/L (Table 2). After treatment in the constructed wetland, nitrogen concentrations decreased significantly to 1.0-4.0 mg/L. Within the wetland, nitrogen transformation occurred simultaneously through nitrification, denitrification, and assimilation by plants and microorganisms [16]. This process resulted in a noticeable reduction in total Kjeldahl nitrogen (TKN) across all three units. Additionally, low TKN levels contained in the effluent reveal that the intermediate nitrification and denitrification products (e.g., NO<sub>2</sub>-N) did not accumulate within the system [17]. CWs have demonstrated high nitrogen removal efficiency in various applications, including municipal wastewater, industrial effluents, and agricultural runoff [18].

#### First-order rate constant

From the experiment, it was observed that the system effectively reduced only color and chemical oxygen demand (COD) from the paper mill effluent (PME). From Table 3, no color removal was shown for cattail unit, only control unit and mangrove unit showed color removal. Thus, the coefficients of the system were specifically analyzed for color (control unit and mangrove unit) and COD using the first-order PFR kinetics equation (2) and first-order CSTR kinetics equation (2) as outlined above.

1) **Color:** The variation in color over time across all eight experimental runs is illustrated in Figure 4. The concentration-time (or distance-from-inlet) plot demonstrates a gradual decrease in pollutant levels over time in the control and mangrove units. This trend suggests that the reaction kinetics may conform to both Plug Flow Reactor (PFR) and Continuous Stirred Tank Reactor (CSTR) models. The first-order reaction rate constants for color treatment, derived from the PFR and CSTR kinetic equations, are summarized in Table 3.



**Figure 4** The relationship between color/COD and the hydraulic residence time of water within the system

**Table 3** Rate constants for according to the first-order plug-flow kinetics

Parameter		Control	Cattail	Mangrove
Color (ADMI)	Influent (mg/L)	118.2-174.7	118.2-174.7	118.2-174.7
	Effluent (mg/L)	119.0-132.3	145.3-187.0	94.3-139.3
	HRT (days)	7	7	7
	$K_{PFR}$ range ( $d^{-1}$ )	0.011-0.050	-	0.003-0.036
	$K_{PFR}$ avg ( $d^{-1}$ )	0.030	-	0.021
	$K_{CSTR}$ range ( $d^{-1}$ )	0.011-0.059	-	0.003-0.038
	$K_{CSTR}$ avg ( $d^{-1}$ )	0.035	-	0.023
COD (mg/L)	Influent (mg/L)	112.0-186.0	112.0-186.0	112.0-186.0
	Effluent (mg/L)	12.0-84.0	20.0-92.0	16.00-88.00
	HRT (days)	7	7	7
	$K_{PFR}$ range ( $d^{-1}$ )	0.053-0.167	0.028-0.319	0.047-0.350
	$K_{PFR}$ avg ( $d^{-1}$ )	0.140	0.131	0.143
	$K_{CSTR}$ range ( $d^{-1}$ )	0.038-2.071	0.024-1.186	0.032-1.518
	$K_{CSTR}$ avg ( $d^{-1}$ )	0.248	0.278	0.291

**2) Chemical oxygen demand (COD):**  
 The variation in COD over time for all 13 experimental runs is depicted in Figure 4. The concentration-time plot shows a notable reduction in COD at the beginning of the tank, characteristic of the CSTR process. The calculated rate constants are presented in Table 3, with average CSTR first-order rate constants of

0.248  $d^{-1}$  for the control unit, 0.278  $d^{-1}$  for the cattail unit, and 0.291  $d^{-1}$  for the mangrove unit.

For vertical flow constructed wetlands (CWs), reaction rate constants reported in literature exhibit significant variation: total nitrogen removal  $k = 0.048-0.19 d^{-1}$ , and  $BOD_5$  removal  $k = 0.071-6.11 d^{-1}$ . These fluctuations likely reflect variations in factors such as bed

matrix composition, porosity, and flow rate, which influence the efficiency of individual processes [19].

## Conclusions

The system effectively reduced some specific pollutants contained in the factory effluent, specifically targeting color (only for the unit planted with mangrove) and COD for such study units. It's somewhat revealed that the system aiding in breaking down complex substances like lignin and nitrogen into more easily degradable forms, thereby increasing organic matter levels as BOD<sub>5</sub>.

Regarding color removal efficiency, the control unit exhibited a range of 0.00-29.39% ( $16.47 \pm 9.86\%$ ), the cattail unit showed 0.00-10.69% ( $3.56 \pm 3.90\%$ ), and the mangrove unit demonstrated 1.74-22.26% ( $14.06 \pm 6.95\%$ ). The control unit and the unit planted with mangrove exhibited better treatment performance than the unit planted with cattail ( $P > 0.05$ ). However, no significant difference in color removal was observed between the control unit and the mangrove unit ( $P > 0.05$ ).

In terms of COD removal efficiency, the control unit ranged from 31.1-93.5% ( $56.9 \pm 18.31\%$ ), the cattail unit ranged from 17.9-89.2% ( $54.3 \pm 21.39\%$ ), and the mangrove unit ranged from 1.7-22.3% ( $14.1 \pm 6.95\%$ ). Both the control and mangrove units demonstrated somewhat higher performance compared to the cattail unit, with statistical significance ( $P > 0.05$ ).

For the first-order rate constant calculation, it was found that.

1) Color: The concentration-time plot demonstrates a gradual decrease in pollutant levels over time, suggesting that the reaction kinetics may conform to both Plug Flow Reactor (PFR) and Continuous Stirred Tank Reactor (CSTR) models. Since no color removal was observed in the cattail unit, reaction rate constants were calculated exclusively for the control and mangrove units. For the mangrove unit, the first-order reaction rate constants were  $0.021 \text{ d}^{-1}$  for the PFR model and  $0.023 \text{ d}^{-1}$  for the CSTR model. For the control unit, the first-order reaction rate constants were  $0.030 \text{ d}^{-1}$  for the PFR model and  $0.035 \text{ d}^{-1}$  for the CSTR model.

2) Chemical Oxygen Demand (COD): The CSTR first-order reaction rate constants

for the control unit were  $0.140 \text{ d}^{-1}$ , for the cattail unit was  $0.131 \text{ d}^{-1}$ , and for the mangrove unit was  $0.143 \text{ d}^{-1}$ . In terms of the CSTR first-order reaction rate constants derived by COD removal. For any units the CSTR first-order reaction rate constants are similar. Constructed wetland, therefore, exhibited significant COD removal and some color removal in the mangrove unit.

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## References

- [1] Stefanakis AI. Introduction to constructed wetland technology. In: John Wiley & Sons; 2018; 1-21.
- [2] Toczyłowska-Mamińska R. Limits and perspectives of pulp and paper industry wastewater treatment—A review. *Renewable and Sustainable Energy Reviews*. 2017; 78: 764-772.
- [3] Wu S, Wallace S, Brix H, Kusch P, Kirui WK, Masi F, Dong R. Treatment of industrial effluents in constructed wetlands: challenges, operational strategies and overall performance. *Environmental Pollution*. 2015; 201: 107-120.
- [4] Abira MA, Van Bruggen JJA, Denny P. Potential of a tropical subsurface constructed wetland to remove phenol from pre-treated pulp and papermill wastewater. *Water Science and Technology*. 2005; 51(9): 173-176.
- [5] Rani N, Singh B, Kumar V. Feasibility of Typha and Canna for pulp and paper mill wastewater treatment through small wetlands. *International Journal of Environmental Sciences*. 2015; 6(3): 388-395.
- [6] Gaballah MS, Abdelwahab O, Barakat KM, Aboagye D. A novel horizontal subsurface flow constructed wetland planted with Typha angustifolia for treatment of polluted water. *Environmental Science and Pollution Research*. 2020; 27: 28449-28462.

- [7] Jesus JM, Calheiros CSC, Castro PML, Borges MT. Feasibility of *Typha latifolia* for high salinity effluent treatment in constructed wetlands for integration in resource management systems. *International Journal of Phytoremediation*. 2014; 16(4): 334-346.
- [8] Ahuja S. *Comprehensive water quality and purification*. Elsevier; 2013.
- [9] Weerakoon GM, Jinadasa K, Manatunge J, Wijesiri B, Goonetilleke A. Kinetic modelling and performance evaluation of vertical subsurface flow constructed wetlands in tropics. *Journal of Water Process Engineering*. 2020; 38: 101539.
- [10] Tchobanoglous G, Crites R, Gearheart B, Reed W. A review of treatment kinetics for constructed wetlands. In: *Disinfection and Reuse Symposium 2000*. 2000; 723-734.
- [11] Samudro G, Mangkoedihardjo S. Review on BOD, COD and BOD/COD ratio: A triangle zone for toxic, biodegradable and stable levels. *International Journal of Academic Research*. 2010; 2(4).
- [12] Yusoff MF, Rozaimah SAS, Hassimi AH, Hawati J, Habibah A. Performance of continuous pilot subsurface constructed wetland using *Scirpus grossus* for removal of COD, colour and suspended solid in recycled pulp and paper effluent. *Environmental Technology & Innovation*. 2019; 13: 346-352.
- [13] Thunga M, Chen K, Grewell D, Kessler MR. Bio-renewable precursor fibers from lignin/poly lactide blends for conversion to carbon fibers. *Carbon*. 2014; 68: 159-166.
- [14] Md Yusoff MF, Abdullah SRS, Hasan HA. Performance of continuous pilot subsurface constructed wetland using *Scirpus grossus* for removal of COD, colour and suspended solid in recycled pulp and paper effluent. *Environ Technol Innov*. 2019. doi:10.1016/j.eti.2018.12.008.
- [15] Parlakidis P, Mavropoulos T, Vryzas Z, Gikas GD. Fluopyram removal from agricultural equipment rinsing water using HSF pilot-scale constructed wetlands. *Environmental Science and Pollution Research*. 2021; 1-13.
- [16] Tanner CC. Nitrogen removal processes in constructed wetlands. In: *Wetlands ecosystems in Asia*. Elsevier; 2004. 331-346.
- [17] Chen TY, Kao CM, Yeh TY, Chien HY, Chao AC. Application of a constructed wetland for industrial wastewater treatment: A pilot-scale study. *Chemosphere*. 2006; 64(3): 497-502.
- [18] Vymazal J, Zhao Y, Mander Ü. Recent research challenges in constructed wetlands for wastewater treatment: A review. *Ecological Engineering*. 2021; 169: 106318.
- [19] Gajewska M, Skrzypiec K, Józwiakowski K, Mucha Z, Wójcik W, Karczmarczyk A, Bugajski P. Kinetics of pollutants removal in vertical and horizontal flow constructed wetlands in temperate climate. *Science of the Total Environment*. 2020; 718: 137371.