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Application of first-order kinetic modelling of municipal wastewater treatment at two stage hybrid constructed wetland

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ABSTRACT

With a focus on naturalistic problem-solving methods, many systems and management techniques that promote high levels of water purity, energy savings, and food security are essential to the expanding green economy. Constructed wetlands are an affordable, dependable, and sustainable substitute for traditional wastewater treatment plants. In this study, a two-stage experimental design was used to establish a hybrid constructed wetland system on a laboratory scale. The vertical flow (VF) constructed wetland was followed by a horizontal flow (HF) constructed wetland. The surface area of the second-stage horizontal flow constructed wetland reactor was 2025 cm², whereas the first-stage vertical flow constructed wetland reactor was 1963.49 cm². The hydraulic loading rate, a crucial factor in the design of two-stage hybrid constructed wetlands, was the main focus of the study, which assessed the effectiveness of these systems. The treatment processes were analyzed using empirical kinetic models, which included two first-order kinetic models: p-k-C and p-k-C* for stage two and k-C and k-C* for stage one. The process operating at a hydraulic loading rate of 0.55 m/day had a beneficial effect on the mass removal rate for both stages. The mass loading rate and mass removal rate were found to have a favorable relation for pollutants, such as total suspended solids, chemical oxygen demand, biochemical oxygen demand, total phosphorus, ammonia nitrogen, and nitrate nitrogen. The nitrification and denitrification processes had less time because of lower oxygenation caused by the high hydraulic loading rate. The design and functionality of two-stage hybrid constructed wetlands could be improved using the valuable insights from this research, leading to more effective wastewater treatment methods.

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1. Introduction

A growing concern is emerging regarding the potential for a "perfect storm" of challenges to develop in the near future, felled by the overlapping and interacting of multiple critical factors. The factors at play encompass the following: a diminishing supply of vital resources, such as water, food, and energy; a growing global population; and a societal transition towards more eco-aware ways of living. The interaction of these elements has highlighted the need for innovative management techniques and systems that improve efficiency, resilience, and sustainability. Solutions that provide high levels of water quality, energy savings, and food security while being in harmony with nature-based techniques are being prioritized in the context of the developing green economy [1, 2]. For rural and peri urban areas, the constructed wetland treatment technique is a novel, cost-effective, and eco-friendly alternative to conventional wastewater treatment. Constructed wetlands provide higher environmental sustainability, increased resilience, and greater cost-effectiveness compared to conventional wastewater treatment models. By using different configurations such as free water surface flow technique, horizontal surface and subsurface flow technique, and vertical subsurface flow technique in a controlled setting, engineered wetland systems are intended to mimic the processes present in naturally occurring constructed wetlands [2-9]. Vertical subsurface flow constructed wetlands have become more common than free water surface flow constructed wetlands and horizontal subsurface flow constructed wetlands because they can treat more wastewater types and require less space [2, 10, 11]. The intermittent feeding mode used in vertical subsurface flow constructed wetlands improves the oxygen movement potential, which results in a more effective removal of various types of pollutants, such as suspended solids, phosphates, ammonium (NH_4^+), and organics (measured by the five-day biochemical oxygen demand and chemical oxygen demand) [8, 10, 12-14]. Various processes, including physicochemical, chemical, and biological methods, are used to effectively remove contaminants from constructed wetlands. These

include nutrient uptake by microorganisms and plants, as well as sedimentation, filtration, adsorption, precipitation, volatilization, biodegradation, nitrification, and denitrification [2, 8, 9, 15, 16]. Plant absorption, adsorption, and microbial degradation are the primary processes that remove organic pollutants and nutrients; these processes often occur simultaneously [8, 16-19].

A number of variables, including the type of wetland, the local climate, and design concerns, influence how well constructed wetlands remove pollutants. Enhancement of constructed wetland are greatly influenced by key hydraulic characteristics such as hydraulic retention time (HRT) and hydraulic loading rate (HLR), as well as influent various pollutant concentrations, vegetation types, substrate media, and microbial communities [2, 8, 9, 14, 16, 19-22]. HRT shows the ratio of usable constructed wetland wastewater volume to the average flow rate, whereas HLR is determined by the ratio of the volumetric flow rate of the wastewater to the surface area of the designed constructed wetland. When assessing the effectiveness of constructed wetland systems, several parameters are essential.

Even with progress in the field, the intricate characteristics of pollutant removal processes and the fluctuating environmental conditions frequently result in constructed wetland designs that rely on experiential knowledge and iterative testing. The absence of standardized design procedures along with the unpredictability of environmental changes has impeded the broader implementation of CWs [19, 21, 23-26]. Throughout the years, a variety of modeling techniques have emerged to enhance our comprehension and forecasting of CW's performance. These models seek to identify relationships between the effectiveness of treatments and essential operational variables.

The first-order kinetic model, commonly described as the Kickuth Equation or k-C model, stands out as one of the most prevalent empirical design methodologies. This model, frequently integrated with plug-flow assumptions, reduces CW systems to a "black box," illustrating the exponential decay of pollutants from the influent wastewater to the effluent wastewater [1, 7, 17, 23, 25, 27-29].

Nonetheless, the k-C model fails to consider the intricate interaction among water, soil, plants, and microbial communities. Furthermore, it does not account for environmental impact elements such as precipitation (ppt) and evapotranspiration (ET), which can produce secondary hydraulic regimes inside the constructed wetland and undercut the efficiency of steady-state models [1, 10, 15, 19].

In response to these limitations, advanced models have been created, such as the plug-flow (PF) dispersion model (dm) and the tanks-in-series (TiS) model. These models replicate non-ideal hydraulic (NIH) conditions and characterize the detention time (DT) distribution in constructed wetlands. Nonetheless, the intricacy and substantial data demands restrict their feasible implementation. As a result, simple first-order kinetic models and basic regression methods continue to be widely used for evaluating CW performance. Researcher Kadlec et al. improved the k-C model to create the k-C* model, which incorporates pollutant degradation and allows for a non-zero background concentration (NZBC) (C^*) to represent the residual effluent pollutant levels once a plateau is reached at the minimize of the treatment process [1, 7, 15, 17, 20, 22, 23, 25]. The k-C* model has garnered significant interest for CW design in recent years.

This study assessed the effectiveness of municipal wastewater treatment (MWWT) using a hybrid constructed wetland (HCW) two-stage system, with an emphasis on rural and semi-peri-urban regions. Through the application of kinetic modelling techniques, the significance of various influent parameters on the efficiency of the hybrid constructed wetland was evaluated. Model optimization aspects that have not been extensively explored in prior studies were also identified. Furthermore, by integrating supplementary response variables, including hydraulic loading rate (HLR), more precise and reliable predictive models were developed. The implications of these findings are substantial for the design, maintenance, and management of hybrid CW systems.

2. Materials and methods

The design of constructed wetland systems has historically depended on empirical knowledge and

established practices primarily because of the intricate nature of pollutant removal processes and the variable local environmental conditions. At present, there are no widely accepted standard practices for the CWs design. In response to this issue, a range of modelling techniques has been established to replicate CW performance by considering the relationships between essential operational parameters and treatment efficiency [8]. The first-order kinetic model, often derived as the k-C model or Kickuth Equation, stands out as the most frequently employed empirical design technique for CW systems. This model, along with plug-flow assumptions, streamlines CW systems by condensing them into a "black box" framework in which contaminants diminish exponentially from the influent (incoming) to the effluent (outflow after treatment) of the system [1, 2, 7, 17, 21, 27]. The k-C model, despite its extensive application, presents specific limitations. It fails to consider the intricate relationships among soil, plants, water, and microbial communities that are crucial for the removal of pollutants. Furthermore, it fails to consider the influence of some environmental factors, like precipitation, evapotranspiration, and temperature variations, which can establish secondary hydraulic regimes within the wetland. According to Gholizadeh et al. [27], Zhou et al. [15], Trang et al. [11], Wu et al. [28], and Sultana et al. [21], the existence of these elements may cause steady-state theoretical models to be inaccurate. In response to some of the above limitations, researchers have developed more advanced models, such as the PF dispersion model (dm) and the tanks-in-series (TiS) model. The purpose of these models is to simulate NIH conditions by detailing the distribution of detention time within the constructed wetland system. The plug-flow dispersion model considers the longitudinal dispersion of pollutants throughout the flow path, whereas the tanks-in-series model envisions the wetland as a sequence of ideal tanks, each symbolizing a segment of the wetland with consistent mixing. Nonetheless, these models exhibit a high level of complexity and necessitate substantial data inputs, which results in their limited application in practical scenarios. Given these challenges, the application of first-order kinetic models and straightforward regression

techniques continues to be common in evaluating CW performance. In acknowledging the necessity for a more refined strategy, Kadlec and Knight adapted the k-C model to create the k-C* model. This model integrates pollutant degradation processes and accommodates a background concentration (C*) that exceeds zero, indicating the residual concentration of pollutants in the effluent once a plateau is achieved toward the conclusion of the treatment process [7, 17, 21, 28, 29].

The design and performance assessment of CW systems frequently employ the k-C* model, which has grown in popularity in recent years.

This investigation was carried out using a hybrid constructed wetland (HCW) two-stage system aimed at treating municipal wastewater. The system comprised a vertical subsurface flow constructed wetland as the initial stage, succeeded by a horizontal subsurface flow constructed wetland as the subsequent stage (Singh et al., 2022). The hybrid system was developed on a laboratory scale, with influent wastewater introduced at a regulated HLR of 0.55 m/day, which demonstrated the ability to enhance pollutant removal efficiency. The two-stage HCW was developed to replicate the natural processes found in full-scale wetlands. The vertical flow in the initial stage facilitates oxygen transfer and the aerobic degradation of organic pollutants, while the horizontal flow in the subsequent stage aids in nutrient removal and the stabilization of residual pollutants. The dimensions of the system were outlined as follows: the vertical subsurface flow constructed wetland (Stage 1) was 1963.49 cm² of surface area, and the horizontal subsurface flow constructed wetland (Stage 2) was 2025 cm² of surface area [8]. The influent wastewater exhibited specific concentrations of biochemical oxygen demand (BOD), chemical oxygen demand (COD), total phosphorus (TP), ammonia nitrogen (NH₄-N), and nitrate nitrogen (NO₃-N). Samples of influent and effluent were systematically collected at regular intervals throughout the operation of the HCW system.

2.1. First order kinetics under the presumption of plug flow (k-C model)

Under the assumption of idealized plug-flow conditions, this model considers the exponential

degradation of various pollutants from the influent wastewater to the effluent wastewater, while establishing a correlation between the influent wastewater and effluent wastewater pollutant concentrations for a single-stage wetland, as demonstrated by Eq. 1 [6, 7, 17, 27].

$$\frac{C_{eff}}{C_{in}} = e^{\frac{-k_1}{HLR}}, k_1 = (\ln C_{in} - \ln C_{eff}) * HLR \quad (1)$$

where k₁= First (1st) order efficacy rate constant in (m/day); C_{in} = Influent (Before treatment) pollutant concentration in (mg/L); C_{eff} = Effluent (After treatment) pollutant concentration in (mg/L); and HLR= Hydraulic loading rate in (m/day).

2.2. First order kinetics modified under the plug-flow presumption (k-C* model)

Kadlec et al., [7, 17], refined the k-C model by incorporating the assumption of exponential pollutant elimination and introducing non zero background constructed wetland concentrations (C*) for a single-stage wetland, as shown in Equation 2. Within the constructed wetland system, leftover material is produced by the biota life cycle and intrinsic biogeochemical cycling, which can be quantified as BOD, COD, nitrogen, phosphorus, and ammonia nitrogen. C* represents an irreducible effluent concentration resulting from the findings of APHA, [30]. Irrespective of the constructed wetland dimensions or the characteristics of the incoming wastewater, there will consistently be residual background levels of these pollutants. Consequently, C* to set a minimum threshold for the effluent quality of a treatment wetland.

$$\frac{(C_{eff}-C^*)}{(C_{in}-C^*)} = e^{\frac{-k_2}{HLR}}, k_2 = [\ln(C_{in} - C^*) - \ln(C_{eff} - C^*)] * HLR \quad (2)$$

where for k-C* model C*= Background concentration in (mg/L) and k₂= First order efficacy rate constant, respectively in (m/day).

2.3. First order kinetics under the presumption of plug-flow (p-k-C model)

A kinetic study was done for municipal wastewater treatment using a hybrid two-stage constructed wetland reactor. In Equation 1, the standard plug-flow equation was employed for the design and modeling of a single stage constructed wetland

treatment system. Due to the constraints of the PF model, wastewater treatment constructed wetland enhancement and performance is most frequently characterized by a modified first order reaction (MFOR) equation based on a non-ideal reactor (NIR) with the assumption that the tank in series is ideal (more than one stage wetland) [17, 27]. Equation 3 shows the kinetic constant for a more than a one stage wetland. In this study, the value of n is 2, signifying that a two-stage hybrid constructed wetland was used.

$$C_{eff} = \frac{C_{in}}{\left(1 + \frac{k'_1}{(n \cdot HLR)}\right)^n}, k'_1 = \left[\left(\frac{C_{in}}{C_{eff}} \right)^{\frac{1}{n}} - 1 \right] * n * HLR \quad (3)$$

where k'_1 = First order efficacy rate constant in (m/day) for p-k-C model; C_{in} = Influent (Before treatment) pollutant concentration in (mg/L); C_{eff} = Effluent (After treatment) pollutant concentration in (mg/L); HLR = Hydraulic loading rate in (m/day); and n = Number of tanks in the series (n=2).

2.4. First order kinetics modified under the presumption of plug-flow (p-k-C* model)

The most recent kinetic equation for characterizing various pollutants in the treatment from constructed wetland is a MFOR equation under a (C^*) non-zero background concentration. The P-k-C* strategy has been shown in Equation 4 to be a good representation of treatment performance of wetlands. The structure of Equation 4 is identical to that of Equation 3, the standard equation for the tank in series. The input and output concentrations are simply subtracted from the background concentration C^* (mg/l). Comprehensive information on horizontal and free water surface flow (FWSF) constructed wetlands, vertical and horizontal flow constructed wetlands, as well as other various design factors including including risk tolerance, seasonal trends in wastewater treatment removal performance, synoptic error (SE), and stochastic variability (SV) including is available [17, 27].

$$\frac{(C_{eff}-C^*)}{(C_{in}-C^*)} = \frac{1}{\left(1 + \frac{k'_2}{(n \cdot HLR)}\right)^n}, k'_2 = \left[\left(\frac{C_{in}-C^*}{C_{eff}-C^*} \right)^{\frac{1}{n}} - 1 \right] * n * HLR \quad (4)$$

where k'_2 = First order efficacy rate constant in (m/day) for p-k-C* model; C_{in} = Influent (Before treatment) pollutant concentration in (mg/L); C_{eff} = Effluent (After treatment) pollutant concentration in (mg/L); HLR = Hydraulic loading rate in (m/day), and n = Number of tanks in series (n=2).

2.5. Mass loading and Mass removal rate determination

The calculations for the mass loading rate (MLR) in $g/m^2/day$ and mass removal rate (MRR) in $g/m^2/day$ for each pollutant were conducted using the equations outlined below:

$$MLR = C_{in} * HLR$$

$$MRR = (C_{in} - C_{eff}) * HLR$$

3. Results and discussion

The kinetic model equations 1 to 4, corresponding to kinetic model k-C, kinetic model k-C*, kinetic model p-k-C, and kinetic model p-k-C* outlined in section 2, were utilized to determine the kinetic reaction rate (KRR) constants k_1 , k_2 , k'_1 , and k'_2 for TSS, BOD, COD, TP, NH_3-N , and NO_3-N . In the two-phase experiment for model k_2 , the non-zero background concentrations (C^*) were derived from the recorded minimum concentrations of TSS (20 and 49 mg/l), BOD (2.7 and 8.8 mg/l), COD (35 and 115 mg/l), TP (1.11 and 1.79 mg/l), NH_3-N (0.093 and 0.9 mg/l), and NO_3-N (0.01 and 0.111 mg/l) in the effluent from phase 1 and phase 2 of the initial stage experimental HCW reactor in this study, following the methodologies of Trang et al. [11] and Babatunde et al. [23]. Similarly for model k'_2 in the two-phase experiment, following the second stage of the HCW reactor configured as tanks in series (n=2), the values of C^* were determined. These C^* values were obtained from the lowest measured value concentrations after Stage 2: TSS (10 and 25 mg/l), BOD (0.9 and 3.2 mg/l), COD (16 and 26 mg/l), TP (0.75 and 0.78 mg/l), NH_3-N (0 and 0.1 mg/l) and NO_3-N (0 and 0.01 mg/l), as observed in the effluent from phase 1 and phase 2 of the Stage 2 experimental HCW reactor. The approach used in this study is similar to those used by other researchers, including Trang et al. [11] and Babatunde et al. [23]. The estimated kinetic reaction rate constant values for TSS, BOD, COD,

NH₃-N, and NO₃-N corresponded to the model at 0.55 m/day HLR.

Table 1 and Figures 1 and 2 show the estimated kinetic reaction rate constant value for model k-C and model k-C* for Stage 1 of the two-stage hybrid constructed wetland reactor. The average kinetic values of TSS, BOD, COD, TP, NH₃-N, and NO₃-N for model k-C were 0.87, 1.36, 0.87, 1.01, 1.78, and 2.21 m/day, respectively, for phase 1. Similarly, for phase 2, the average kinetic values were 0.98, 1.23, 0.61, 1.28, 1.35, and 1.99 m/day, respectively, as shown in Figure 1.

The kinetic values of TSS and TP for model k-C in phase 2 increased, while BOD, COD, NH₃-N, and NO₃-N decreased, confirming that the constructed wetland bed (CWB) potentially enhanced

nitrification and minimized denitrification rates, as well as good removal of organic matter. These conditions were similar to those reported by Trang et al. [11] and Babatunde et al. [23].

For model k-C*, the average kinetic value of TSS, BOD, COD, TP, NH₃-N, and NO₃-N for phase 1 were 1.22, 1.69, 1.22, 1.44, 1.84, and 2.2 m/day, respectively the average kinetic values for phase 2 were 1.58, 2.01, 1.38, 2.31, 1.87, and 2.57 m/day, respectively (Figure 2). The kinetic value of TSS, BOD, COD, TP, NH₃-N, and NO₃-N for model k-C* in phase 2 increased, indicating that the hybrid constructed wetland may not be easily described as a modified plug flow (PF) reactor at Stage 1 for a two-stage hybrid constructed wetland reactor [1].

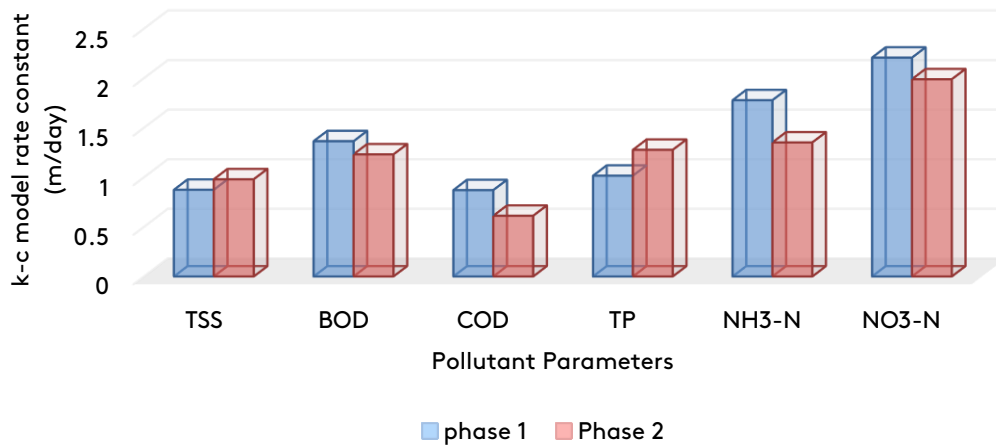


Fig. 1. k-c model rate constants for Stage 1 of a two-stage hybrid constructed wetland design and performance monitoring (n=1).

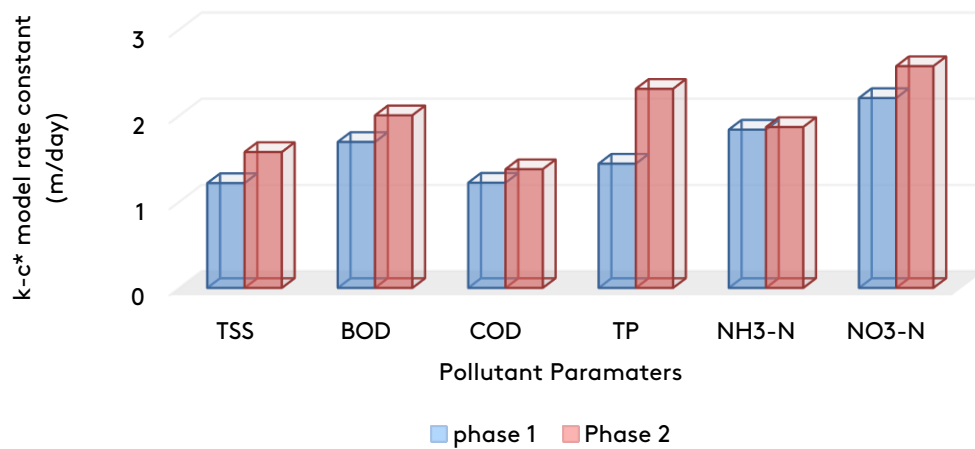


Fig. 2. k-c* model rate constants for Stage 1 of a two-stage hybrid constructed wetland design and performance monitoring (n=1).

Table 1. KRR constants for Stage 1 of a two-stage hybrid constructed wetland design and performance monitoring.

Parameters	Kinetic model	Unit	Average value	Maximum	Minimum	Standard deviation
Phase 1 Kinetic study (n=1)						
TSS	k-C model	m/day	0.87	1.52	0.24	0.33
	k-C* model	m/day	1.22	3.01	0.28	0.62
BOD	k-C model	m/day	1.36	2.03	-0.09	0.47
	k-C* model	m/day	1.69	3.43	-0.09	0.74
COD	k-C model	m/day	0.87	1.39	0.17	0.28
	k-C* model	m/day	1.22	3.29	0.19	0.59
TP	k-C model	m/day	1.01	1.37	0.42	0.31
	k-C* model	m/day	1.44	2.58	0.52	0.51
NH ₃ -N	k-C model	m/day	1.78	2.66	0.88	0.41
	k-C* model	m/day	1.84	3.13	0.71	0.49
NO ₃ -N	k-C model	m/day	2.21	3.62	0.64	1.13
	k-C* model	m/day	2.20	4.02	0.64	1.31
Phase 2 Kinetic study, (n=1)						
TSS	k-C model	m/day	0.98	1.24	0.62	0.13
	k-C* model	m/day	1.58	2.92	0.86	0.39
BOD	k-C model	m/day	1.23	1.40	1.02	0.08
	k-C* model	m/day	2.01	3.09	1.31	0.39
COD	k-C model	m/day	0.61	0.74	0.43	0.06
	k-C* model	m/day	1.38	2.33	0.54	0.32
TP	k-C model	m/day	1.28	1.43	1.12	0.07
	k-C* model	m/day	2.31	3.51	1.37	0.34
NH ₃ -N	k-C model	m/day	1.35	1.61	1.20	0.09
	k-C* model	m/day	1.87	3.07	1.56	0.28
NO ₃ -N	k-C model	m/day	1.99	2.38	1.63	0.17
	k-C* model	m/day	2.57	3.49	1.83	0.45

The kinetic reaction rate (KRR) constant values for each pollutant parameters were optimized using model p-k-C and model p-k-C* in the two-stage hybrid constructed wetland. In the two-stage HCW, the treatment process for each pollutant parameter was modeled as two tanks in series (n = 2). Table 2 shows the estimated kinetic reaction rate constant values for model p-k-C and model p-k-C* for a two-stage hybrid constructed wetland reactor (n=2 tank in series). The average kinetic values of TSS, BOD, COD, TP, NH₃-N, and NO₃-N for model p-k-C were 2.46, 5.2, 2.63, 2.36, 16.49, and 16.89 m/day, respectively, for phase 1 and 2.59, 4.05, 2.42, 4.07, 8.73, and 16.81 m/day, respectively, for phase 2 (Figure 3). The kinetic values of TSS and TP for model p-k-C in phase 2 increased, while BOD, COD, NH₃-N, and NO₃-N decreased, which confirmed that CWB was potentially associated with enhanced nitrification and minimized denitrification rates, as well as good removal of organic matter after the two-stage treatment. For the p-k-C* model, the average kinetic values of TSS, BOD, COD, TP, NH₃-N, and

NO₃-N for phase 1 were 3.44, 7.64, 3.12, 4.11, 16.49 and 16.89 m/day, respectively, and the average kinetic values for phase 2 were respectively 5.51, 8.4, 5.27, 11.59, 10.28, and 19.96 m/day (Figure 4). The kinetic values of TSS, BOD, COD, TP and NO₃-N for model p-k-C* in phase 2 increased, while NH₃-N decreased which indicated that HCW cannot be simply described as a modified PF reactor for a two-stage HCW reactor when tank in series [7, 17, 29].

Table 3 shows the average MLR, MRR, and C* values for TSS, BOD, COD, TP, NH₃-N, and NO₃-N at 0.55 m/day HLR for phases 1 and 2. It is clear that 0.55 m/day HLR has a good effect on both phase 1 and phase 2 MRR. The MLR has an extremely close relationship with the MRR for TSS, BOD, COD, TP, NH₃-N, and NO₃-N. Therefore, it is safe to say that low levels of oxygen are also good for removing all parameters in a two-stage hybrid-built wetland. But the two-stage hybrid wetland reactor that worked at an HLR of 0.55 m/day showed that MLR and MRR were well related. This could be because there was less time for nitrification and

denitrification to occur, because the higher HLR made the air less oxygenated

Table 2. KRR constants for Stage 2 of a two-stage hybrid constructed wetland design and performance monitoring.

Parameters	Kinetic Model	Unit	Average value	Maximum	Minimum	Standard deviation
Phase 1 Kinetic study, (n=2)						
TSS	p-k-C model	m/day	2.46	5.86	0.50	1.27
	p-k-C* model	m/day	3.44	8.61	0.56	2.15
BOD	p-k-C model	m/day	5.20	10.28	0.03	2.60
	p-k-C* model	m/day	7.64	20.37	0.03	5.40
COD	p-k-C model	m/day	2.63	4.67	0.85	1.26
	p-k-C* model	m/day	3.12	4.56	0.98	1.35
TP	p-k-C model	m/day	2.36	3.91	0.69	0.51
	p-k-C* model	m/day	4.11	9.75	0.83	1.48
NH ₃ -N	p-k-C model	m/day	16.49	98.75	0.92	17.88
	p-k-C* model	m/day	16.49	98.75	0.92	17.88
NO ₃ -N	p-k-C model	m/day	16.89	34.40	1.35	11.01
	p-k-C* model	m/day	16.89	34.40	1.35	11.01
Phase 2 Kinetic study, (n=2)						
TSS	p-k-C model	m/day	2.59	3.64	1.54	0.51
	p-k-C* model	m/day	5.51	12.22	2.25	2.81
BOD	p-k-C model	m/day	4.05	5.32	2.68	0.64
	p-k-C* model	m/day	8.40	35.23	3.56	4.94
COD	p-k-C model	m/day	2.42	3.48	1.25	0.50
	p-k-C* model	m/day	5.27	14.76	1.58	3.06
TP	p-k-C model	m/day	4.07	5.03	3.32	0.41
	p-k-C* model	m/day	11.59	45.44	4.34	5.95
NH ₃ -N	p-k-C model	m/day	8.73	13.76	4.90	2.85
	p-k-C* model	m/day	10.28	13.72	5.46	2.81
NO ₃ -N	p-k-C model	m/day	16.81	29.01	7.80	6.98
	p-k-C* model	m/day	19.96	42.69	8.50	8.85

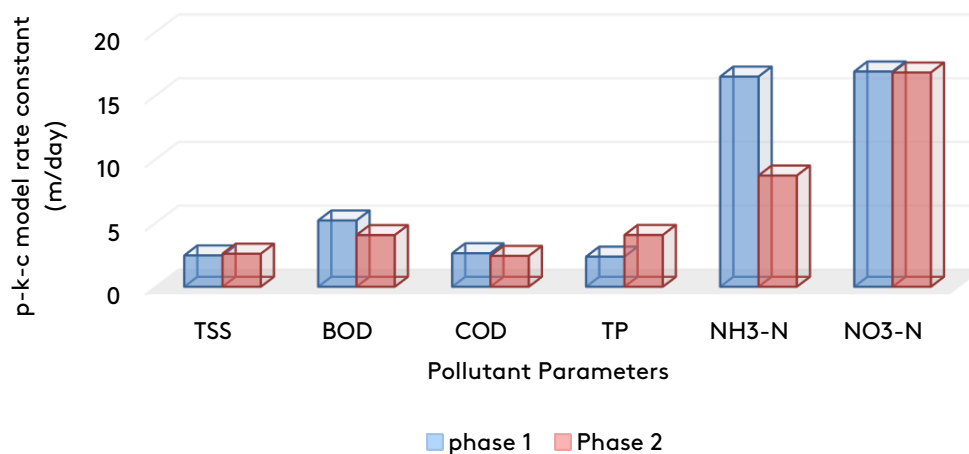


Fig. 3. p-k-c model rate constants for the two-stage hybrid constructed wetland design and performance monitoring (n=2).

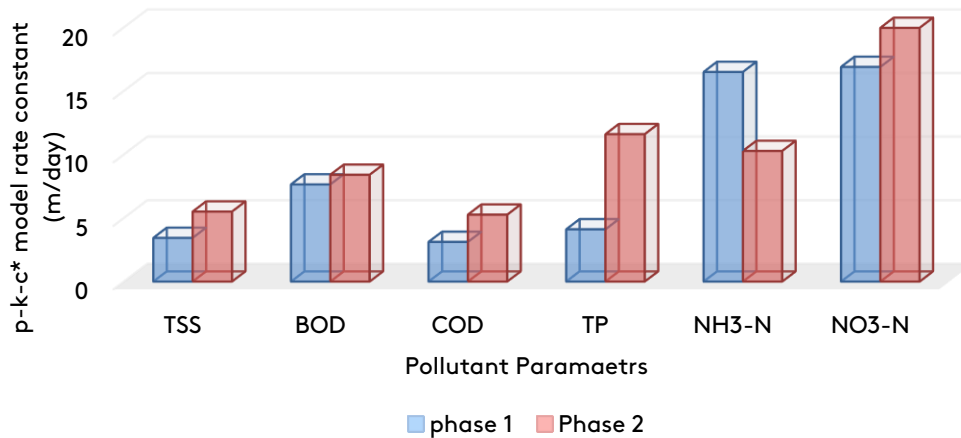


Fig. 4. p-k-c* model rate constants for the two-stage hybrid constructed wetland design and performance monitoring (n=2).

4. Conclusion

The results showed a maximum rate of organic matter and maximum nutrient removal, suggesting that using HCW can be an effective way to treat sewage. The results of the model evaluation showed that HLR was a significant parameter in designing a two-stage hybrid constructed wetlands using empirical kinetic models. Two first order kinetic models, k-C, and k-C*, were applied for stage one in a two-stage reactor. For the second stage, two first order kinetic models—p-k-C and p-k-C*—were used with tanks in a series in two-stage reactors.

The design of a two-stage hybrid CW was evaluated using laboratory-scale experimental configurations operated at 0.55 m/day HLR. When tanks were in series (n=2), the results showed that for model p-k-C*, the average kinetic value of TSS, BOD, COD, TP, NH₃-N, and NO₃-N for phase 1 were 3.44, 7.64, 3.12, 4.11, 16.49, and 16.89 m/day, respectively. The results showed that at 0.55 m/day, HLR had a good effect on both phase 1 and phase 2 MRR. The MLR had an extremely close relationship with the MRR for TSS, BOD, COD, TP, NH₃-N, and NO₃-N. Possibly because there was less time for nitrification and denitrification to occur since the higher HLR made the air less oxygenated.

Author's contribution

Krishna Kumar Singh contributed to the manuscript study setup installation, methodology, experimental data collection, data analysis, and manuscript preparation. **Rakesh Chandra Vaishya** supervised the final setup installation, data validation, and final manuscript preparation, as well as providing resources.

Conflict of interest

No potential conflict of interest was reported by the authors.

Data availability

This published manuscript contains all of the data generated and examined during this evaluation.

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