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Mathematical models of a fluidized bed bioreactor using granular activated carbon (FBBR-GAC) for wastewater treatment

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Abstract

This study aimed to develop mathematical models of a novel recirculation plug-flow reactor (RPFR) and recirculation completely-mixed stirred tank reactors (RCSTR). It was done evaluate and predict wastewater treatment performance using a fluidized bed bioreactor with granular activated carbon (FBBR-GAC). Wastewaters from household washing activities and from an industrial dairy process were used in these experiments. The highest COD removal (>90%) from the two wastewaters were achieved at recirculation ratio (R) of 936. The kinetic results showed that the rate of COD removal from the two types of wastewater used with FBBR-GAC reactors followed 2nd order kinetic models, with $k_{2,RPFR}$ values of 4.68 x 10^{-2} and 2.81 x 10^{-2} mg^{-1} $Ld^{-1}$for washing and dairy wastewaters, respectively. Additionally, we found that the RPFR model was more suitable for describing the behavior of the FBBR-GAC system than the RCSTR model. The developed RPFR model can precisely predict the effluent COD of wastewater at the optimum rate of recirculation (R) 936, and optimum rate of the bed's stirrer speed (N_B) 25 rpm. Based on the optimum R and kinetic model, the developed RPFR model can be used to predict the COD reduction overtime. For a continuous process, an optimal flowrate can be obtained from the HRT that gives the desired COD removal at a given reactor volume.

Keywords: Mathematical models, Recirculation bioreactor, Granular activated carbon (GAC), Wastewater

1. Introduction

In the recent years, as population grows, urbanization and industrialization have gradually increased resulting in unforeseen water crises. These are major problems around the world. Thailand, a developing country, has started to become aware of the water pollution from both domestic and industrial activities [1]. Many sectors, including the communities, government, and private organizations, are concerned about this issue. It is tremendously important to develop reliable and low cost processes with a small footprint for domestic and small scale industrial wastewater treatment technologies. Central wastewater treatment systems require a considerable initial investment and large area for operation. Moreover, in suburban areas and in small scale industries, relatively small quantities of wastewater are generated that are located far from each other. This makes it unfeasible to collect wastewater for a central wastewater treatment plant. The wastewater generated from suburban areas or small industries located outside an industrial park require small to medium scale wastewater treatment plants that can treat a high COD concentration and meet effluent standards, e.g., 120 mg/L COD.

In order to respond these needs, a fluidized bed bioreactor-granular activated carbon (FBBR-GAC) is considered a most suitable technology [2-4]. The FBBR-GAC is a simple wastewater treatment process utilizing adsorption-biodegradation through GAC that was adapted from the conventional fluidized bed biofilm reactor (FBBR). FBBR-GAC was designed to be simple, friendly-user, but it becomes highly effective when using granular activated carbon (GAC) as a medium to increase the efficiency of adsorption and biodegradation. According to a previous study by Suksomboon and Junsiri (2018) [4], a FBBR-GAC was successfully applied for processing primary treated sewage effluent (PTSE) (COD≈2000 mg/L). The FBBR-GAC exhibits several advantages over other conventional processes such as trickling filters (TF) and activated sludge

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(AS) [5-7]. The advantages of this system include (i) effective immobilization of microorganisms on a small porous fluidized medium, GAC, that leads to a higher biomass concentration than those of AS, (ii) high hydraulic residence time (HRT) resulting high treatment efficiency, (iii) the upward flow in a FBBR-GAC can minimize bed clogging, high-pressure drop, poor mixing, and increase oxygen transfer, which are frequently found in a TF, and, (iv) biofilms form in the supporting carrier yielding a large specific biofilm surface area that can lead to a higher rate of COD removal [8-10].

Granular activated carbon (GAC) plays an important role in adsorption-biodegradation. It is a medium that has been widely used in both domestic and industrial wastewater treatment systems as it allows for simple design, the required small footprint, better tolerance of fluctuations of influent characteristics compared to other conventional biological treatment processes [11]. With the combined adsorption-biodegradation process using a fluidized bed bioreactor, an FBBR-GAC system offers high performance with a small footprint. It was found that GAC had a specific biofilm surface area approximately 1,600-2,000 m^2/m^3 [12] leading to high growth rate of microorganisms on the biofilm surface and in internal pores, and high tolerance of organic loads during adsorption-biodegradation.

Most of the studies on chemical oxygen demand (COD) removal by adsorption- biodegradation processes with various adsorbents did not address the fundamental questions needed to implement this technology on a practical basis. In a FBBR-GAC, fluid flow has two components, a rising flow and a rotational flow. Effectively, the fluid flows in an upward spiral [4]. Since the FBBR-GAC reactor is a cylindrical acrylic tank containing GAC that uses a high degree of recirculation, hydraulic retention time (HRT) and hydraulic recirculation time (HReT) are very important design criteria for this system [4, 7, 9]. Thus the optimum R (HReT/HRT) for a continuous process or V_{Re}/V for batch process) is considered an important parameter for the performance of the system.

The working principle of FBBR-GAC reactors has some similarities with a plug flow reactor (PFR) and a completely-mixed stirred tank reactor (CSTR) [13-15]. These two systems are widely used and modelled, but there is no mathematical model of wastewater treatment for a FBBR-GAC process in the literature. Therefore, this study aimed to develop novel mathematical models based on a recirculation plug-flow reactor (RPFR) and recirculation completely- mixed stirred tank reactor (RCSTR) . Furthermore, the study evaluates the models to determine which is more accurate in predicting COD reduction over time in a FBBR-GAC system. The model can be used to evaluate the kinetics of adsorption-biodegradation of COD in wastewater treatment from two sources, a washing activity and industrial dairy processing.

2. Materials and methods

2.1 Fluidized bed bioreactor using granular activated carbon (FBBR- GAC)

The FBBR-GAC used in the current study is a cylindrical acrylic tank with a volume of 12.2 L that contains 4 kg of GAC. The GAC (FILTRASORB 100) was obtained from Calgon Carbon (PA, USA) with an iodine number of 850 mg/g. An impact nozzle water jet was used to impinge upon and turn a twenty-four wheel impeller. The stirring speed was controlled by adjusting the rate of recirculation flow (Q_{Re}) and inflow rate (Q_{in}) to get the best diffusion in the bed. The percentage distribution of bed (D.B.%) was higher than 95% which was caused by the impact of water jet nozzles on the stirred GAC (see Figure 1A). Figure 1B illustrates the spiral flow of wastewater from the initial height of saturated bed (h_0). It is caused by the water from recirculation flow (Q_{Re}) and its impact through a water jet nozzle on wheels that induce rotational flow. This flow also expands the bed of GAC and fluidizes it to a bed height of h_B. The total of both heights is the height of the expanded bed (h_e). Above the GAC, there is a layer of wastewater that has no activated carbon. Its height is h_{water}, as depicted in Figure 1B. The percent of distribution of bed (D.B.%) is calculated from the height of the expanded bed (h_e) and the height of excessive water level (h_{water}) as shown in Eq. (1):

$$\%DB = \frac{h_e}{h_{Water}} x100 \tag{1}$$

Figure 1C illustrates the three dimensional flow in this reactor with both rotational and vertical components. It consists of an upward flow of the bed as shown in Figure 1D. The vertical speed of liquid through bed (u_V) is calculated from the increased height of the bed (h_B) divided by the time that it takes the liquid to move through the bed (t_B). The calculated total speed (u) is a function of the angular speed of the bed (θ_B) and the upward flow rate [16]. Eq. (2) shows the relationship between the speed of bed (u) and the vertical speed of bed (u_V). Eq. (2) relates the angular speed of bed (θ_B) and the reactor diameter (D_R) to the bed's stirrer speed (N_B) [17]:

$$N_B = \frac{30h_B}{A_R(t_B)Sin(\theta_B)} x100 \tag{2}$$

where N_B is the bed's stirrer speed (rpm), A_R is the cross-sectional area of the reactor (m^2).

$h_B = 0.004Q_{\mathrm{Re}}^{0.948}W_{Dry}{}^{0.671}$ is the increase of bed height (m),

$t_B = 19.24Q_{\mathrm{Re}}^{-0.30}W_{Dry}{}^{0.218}$ is the time movement of the bed (seconds)

$\theta_B = 4431.35Q_{\mathrm{Re}}^{-2.59}W_{Dry}{}^{0.11Q_{\mathrm{Re}}^{1.01}}$ is the angular speed of the bed (degrees)

2.2 Developing mathematical models

The fluidized bed bioreactor–granular activated carbon (FBBR- GAC) was developed from the fluidized bed bioreactor (FBBR) concept. However, its operation combines the processes of a plug flow reactor (PFR) and a completely mixed stirred tank reactor (CSTR), which are classified as ideal reactors. Therefore, this study employed mathematical models of these two ideal reactors [18] to develop two new mathematical models for predicting the performance of a FBBR and then determining which model is the most suitable [4].

2.2.1 Recirculation plug-flow reactor (RPFR)

Plug flow reactor (PFR) models can be classified based on various configurations [18]. The PFR reactor or the tubular reactor is sometimes called a piston flow or a perfect

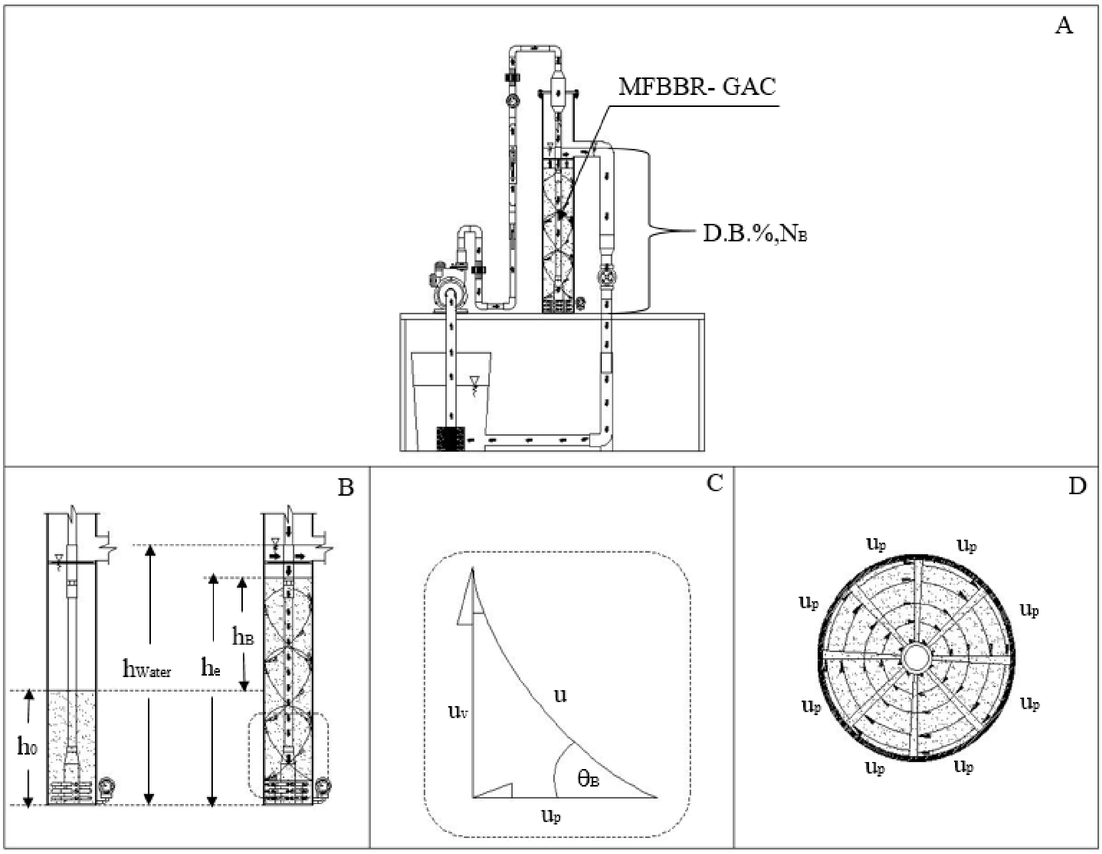

Figure 1 (A) Profile of a FBBR-GAC, (B) hydraulic characteristics of FBBR-GAC [4], (C) velocity of bed flow, (D) characteristics bed flow in the upward direction

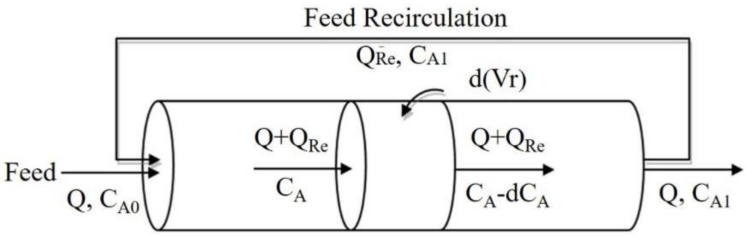

Figure 2 Recirculation plug-flow reactor (RPFR)

flow reactor. It consists of a long cylinder that enables a consistent and unmixed forward movement of mass.

Fluid is continuously fed into the reactor, similar to a completely-mixed flow reactor [13-15]. The developed model is used to simulate the effect of recirculation behaviors of flow and demonstrate the performance of the wastewater treatment mechanisms using a rate coefficient, k, for COD removal.

The COD concentration is changed in the direction of flow over time. Therefore, in a RPFR, the composition of the fluid varies from point to point along the flow path. The continuity equation is expressed as a partial differential equation that shows concentration changes over a unit of time for each fluid element within the specific volume in the direction of flow, as shown in Figure 2 [18].

A recirculation plug flow reactor (RPFR) operated at steady-state is shown in Figure 2. A mass balance for a reaction component must be made for a differential volume, d(Vr), as shown in this figure. The recirculation mass-balance, Eq. (3), for steady state becomes:

[Input] = [Output] + [Decrease due to recirculation reaction] (3)

The recirculation material balance for component A in differential reactor volume, dVr, is therefore:

$$(Q+QR)C_A = (Q+QR)(C_A - dC_A) + r_A d(Vr) \quad (4)$$

Note that R represents Q_{Re}/Q from which

$$(Q+QR)dC_A = r_A d(Vr) \quad (5)$$

Considering a first-order, irreversible reaction:
$r_A = -k_{1^{st}-RPFR} C_{A1}$,

Rearranging for integration results in:

$$(Q+QR)dC_A = -k_{1^{st}-RPFR} C_A d(V_r) \quad (6)$$

$$\frac{dC_A}{C_A} = -\frac{k_{1^{st}-RPFR}}{(Q+QR)} d(V_r) \quad (7)$$

Integration yields:

$$\int_{C_{A0}}^{C_{A1}} \frac{dC_A}{C_A} = -\frac{k_{1^{st}-RPFR}}{Q+QR} \int_0^{V_r} d(V_r) \quad (8)$$

$$ln\left(\frac{C_{A1}}{C_{A0}}\right) = -k_{1^{st}-RPFR}\left[\frac{V_r}{Q+QR}\right] \quad (9)$$

Vr $= Qt_{PFR}$; t_{PFR} is the hydraulic retention time (HRT) of the fluid

$$ln\left(\frac{C_{A1}}{C_{A0}}\right) = -k_{1^{st}-RPFR}\left[\frac{Qt_{PFR}}{Q+QR}\right] \quad (10)$$

$$ln\left(\frac{C_{A1}}{C_{A0}}\right) = -k_{1^{st}-RPFR}\left[\frac{t_{PFR}}{1+R}\right] \quad (11)$$

$$C_{A1} = C_{A0}e^{-k_{1^{st}-RPFR}(t_{PFR}/(1+\mathrm{R}))} \quad (12)$$

Therefore, the solution for the rate constant of recirculation plug-flow reactor (RPFR) is given by:

$$k_{1^{st}-RPFR} = \frac{-ln\left(\frac{C_{A1}}{C_{A0}}\right)}{(t_{PFR}/(1+R))} \quad (13)$$

For a second-order, irreversible reaction:

$r_A = -k_{2^{nd}-RPFR}C_A^2$, rearranging for integration results in:

$$(Q+QR)dC_A = -k_{2^{nd}-RPFR}C_A^2 d(V_r) \quad (14)$$

$$\frac{dC_A}{C_A^2} = -\frac{k_{2^{nd}-RPFR}}{Q+QR} d(V_r) \quad (15)$$

Integration yields:

$$\int_{C_{A0}}^{C_{A1}} \frac{dC_A}{C_A^2} = -\frac{k_{2^{nd}-RPFR}}{Q+QR} \int_0^{V_r} d(V_r) \quad (16)$$

$$\frac{1}{C_{A0}} - \frac{1}{C_{A1}} = -k_{2^{nd}-RPFR}\left[\frac{V_r}{Q+QR}\right] \quad (17)$$

where:
Vr $= Qt_{PFR}$; t_{PFR} is the hydraulic retention time (HRT) of the fluid

$$\frac{1}{C_{A0}} - \frac{1}{C_{A1}} = -k_{2^{nd}-RPFR}\left[\frac{Qt_{PFR}}{Q+QR}\right] \quad (18)$$

$$\frac{1}{C_{A0}} - \frac{1}{C_{A1}} = -k_{2^{nd}-RPFR}\left[\frac{t_{PFR}}{1+R}\right] \quad (19)$$

Therefore, the solution for the concentration of recirculation plug-flow reactor (RPFR) is given by:

$$C_{A1} = \frac{\mathrm{C}_{A0}}{[1+\mathrm{C}_{A0}\mathrm{k}_{2^{nd}-RPFR}(\mathrm{t}_{PFR}/(1+\mathrm{R})]} \quad (20)$$

Therefore, the solution for the rate constant of recirculation in a plug-flow reactor (RPFR) is given by:

$$k_{2^{nd}-RPFR} = \frac{(1/\mathrm{C}_{A1}-1/\mathrm{C}_{A0})}{\left(\frac{\mathrm{t}_{PFR}}{1+R}\right)} \quad (21)$$

2.2.2 Recirculation completely-mixed stirred tank reactor (RCSTR)

The completely-mixed stirred tank reactor (CSTR) is one that feeds fluid in and discharges fluid at the same time at a steady state flow as depicted in Figure 3 [13-15]. Employing recirculation at a flowrate (Q_{Re}) can decrease the initial COD and increase the performance of wastewater treatment operation. The feed fluid and recirculation fluid are almost instantaneously mixed with the fluid already present, and the concentration is uniform throughout the entire reactor volume. As a result of mixing, the composition of the discharge stream is the same as that of the contents in the reactor. Mixing in a RCSTR is significant, and it is assumed that the fluid in the reactor is perfectly mixed so that the contents are uniform throughout the reactor volume.

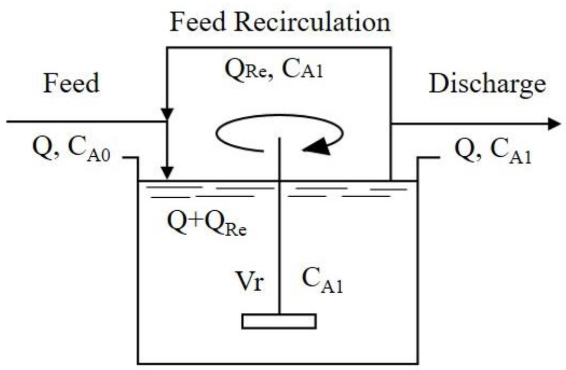

Figure 3 Recirculation completely- mixed stirred tank reactor (RCSTR)

For the RCMFR or RCSTR the recirculation mass-balance Eq. (22), for the reactor is:

[Accumulation] = [Input]-[Decrease due to recirculation reaction]-[Output] (22)

Considering a RCSTR as a first-order recirculation reactor, the rate of reaction is $r_A = -k_{1^{st}-RCSTR}\, C_{A1}$. Substituting this into the recirculation mass-balance equation yields:

$$V_r dC_{A1} = C_{A0}(Q+QR)dt - (V_r)k_{1^{st}-RCSTR}\, C_{A1}dt - C_{A1}(Q+QR)dt \quad (23)$$

Note that R represents Q_{Re}/Q and can be rearranged to yield:

$$\frac{V_r}{(Q+QR)}\frac{dC_{A1}}{dt} = C_{A0} - \frac{(V_r)}{(Q+QR)}k_{1^{st}-RCSTR}C_{A1} - C_{A1} \quad (24)$$

For steady state, $\frac{dC_{A1}}{dt} = 0$.

$$0 = C_{A0} - \frac{(V_r)}{(Q+QR)}k_{1^{st}-RCSTR}C_{A1} - C_{A1} \quad (25)$$

where:
Vr $= Qt_{CSTR}$; t_{CRTR} is the hydraulic retention time (HRT) of the fluid.

$$0 = C_{A0} - \frac{(\mathrm{Q}t_{CSTR})}{(Q+QR)}k_{1^{st}-RCSTR}C_{A1} - C_{A1} \quad (26)$$

Table 1 General industrial wastewater characteristics [9]

Wastewater	pH	T, ^{0}C	BOD5, (mg/l)	COD, (mg/l)	TSS, (mg/l)	TKN, (mg/l)	O&G, (mg/l)	N, (mg/l)	Others, (mg/l)
Slaughterhouse	6–8.5	26–34	500–750	2000–2500	1000	15–300	150–250	10–190	NA
Tobacco	4–5.5	NA	760–4200	4500–11800	140–600	NA	10–40	NA	NA
Starch	6–7	NA	2700	41000	23000	NA	15	NA	2 (phenol)
Distillery (molasses as feed)	3.5–4	NA	59000 −120000	100000–150000	1000–2000	NA	NA	1200	NA
Paper (recycled paper as product)	7–9	40–60	1550	2770	200	NA	10	NA	800 (TDS)
Brewery	NA	18–40	800–1600	1250–2550	150–500	25–35	NA	NA	20–30 (PO-P4)
Soft drink	5.5–10.5	35	600	1440	45	NA	80	3	35 (detergent)
Fast food kitchen	6.2–8.9	NA	300–690	770–1550	220–580	NA	50–190	NA	NA
Noodles/Vermicelli	4–10	25–30	410–1050	1000–2000	200	NA	20–800	NA	1000 (TDS)
Seafood (fish)	6	18–25	750	1440	350	NA	NA	NA	25 (TN)
Dairy (milk)	6–8	30–40	480	920	120	NA	250	NA	85 (TN)
Coffee (decaffeinated)	4–6.5	36–42	2660	4800	1000	NA	20–170	NA	NA
Chili & soya sauce	4.5	30–45	5000	10000	800	NA	NA	NA	15 (TN)
Personal care (shampoo)	6–7.3	NA	500–800	2000–3400	30–40	NA	400	NA	NA
Pharmaceutical (antibiotics & vitamins)	6–7	NA	100–1020	150–1820	300	NA	NA	NA	15–30 (TN) 20 (sulphide) NA

from which:

$$0 = C_{A0} - \frac{(t_{CSTR})}{(1+R)} k_{1^{st}-RCSTR} C_{A1} - C_{A1} \tag{27}$$

Solving:

$$C_{A1} - C_{A0} = -(t_{CSTR}/(1+R))k_{1^{st}-RCSTR} C_{A1} \tag{28}$$

Therefore, the solution for the concentration of recirculation continuously stirred tank reactor (RCSTR) is given by:

$$\frac{C_{A1}-C_{A0}}{C_{A1}} = -k_{1^{st}-RCSTR}(t_{CSTR}/(1+R)) \tag{29}$$

Therefore, solving for the rate constant (k) of recirculation for a RCSTR is given by:

$$k_{1^{st}-RCSTR} = -\left[\frac{C_{A1}-C_{A0}}{(t_{CSTR}/(1+R))C_{A1}}\right] \tag{30}$$

For the second- order recirculation reactor, the rate of reaction is $r_A = -k_{2^{nd}-RCSTR}\, C_{A1}^2$. Substituting this into the recirculation mass-balance equation yields:

$$V_r dC_{A1} = C_{A0}(Q+QR)dt - (V_r)k_{2^{nd}-RCSTR}\, C_{A1}^2 dt - C_{A1}(Q+QR)dt \tag{31}$$

Rearranging results in:

$$\frac{V_r}{(Q+QR)}\frac{dC_{A1}}{dt} = C_{A0}dt - \frac{(V_r)}{(Q+QR)} k_{2^{nd}-RCSTR}\, C_{A1}^2 dt - C_{A1}dt \tag{32}$$

For steady state, $\frac{dC_{A1}}{dt} = 0$.

$$0 = C_{A0} - \frac{(V_r)}{(Q+QR)} k_{2^{nd}-RCSTR}\, C_{A1}^2 - C_{A1} \tag{33}$$

where:
Vr $= Qt_{CSTR}$; t_{CSTR} is the hydraulic retention time (HRT) of the fluid.

$$0 = C_{A0} - \frac{(Qt_{CSTR})}{(Q+QR)} k_{2^{nd}-RCSTR}\, C_{A1}^2 - C_{A1} \tag{34}$$

$$0 = C_{A0} - \frac{(t_{CSTR})}{(1+R)} k_{2^{nd}-RCSTR}\, C_{A1}^2 - C_{A1} \tag{35}$$

Therefore, the solution for the rate constant (k) of recirculation continuously stirred tank reactor (RCSTR) is given by:

$$k_{2^{nd}-RCSRT} = -\left[\frac{C_{A1}-C_{A0}}{(t_{CSTR}/(1+R)C_{A1}^2}\right] \tag{36}$$

2.3 Kinetic experiments

2.3.1 Domestic and industrial wastewaters

Domestic wastewater is the wastewater discharged from residences. Generally, it can be classified into two categories. These are brown wastewater (kitchen, bath, laundry) and black wastewater (urine, feces and toilet paper) [19]. The studies of Haribabu and Sivasubramanian [20-21] of domestic wastewater revealed that it is characterized by COD in the range of 910–7,500 mg/l. Industrial wastewaters are those generated from raw material processing and manufacturing. Some of the reported characteristic values of these wastewaters are listed in Table 1. Wastewaters have varied compositions depending on the type of industry and its raw materials. Some of these are easily biodegradable, organically very strong, or are largely inorganic which result in large values of BOD5, COD, and total suspended solids (TSS) [1]. Their pH values are generally between 6 and 9. In this study, the wastewater from a dairy was collected and used through the experiments.

2.3.2 Kinetic studies and modelling

For kinetic our studies, the rate of COD reduction of two types of wastewater, household wastewater (from washing) and wastewater from a dairy process, were investigated. The decreased COD concentration in each wastewater was determined at times of 10, 20, 30, 60, 90, 120 and 150 mins. The kinetics of COD reduction were proposed by various models. Pseudo first and second order reactions are given in equations 37 and 38, respectively:

$$r = -\frac{dC}{dt} = -k_1 C \quad \rightarrow \quad \ln[C_0] - \ln[C] = k_1 t \tag{37}$$

$$r = -\frac{dC}{dt} = -k_2 C^2 \quad \rightarrow \quad \frac{1}{C_0} - \frac{1}{C} = -k_2 t \tag{38}$$

where, C_0 is initial concentration of COD and C_t is concentration of COD at time of reaction. The k_n is an n-order rate constant, that can be expressed in a linear form versus time.

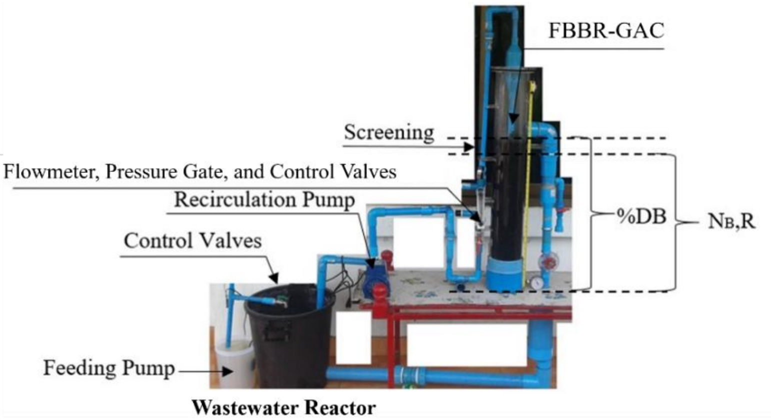

Figure 4 The fluidized bed bioreactor–granular activated carbon (FBBR-GAC)

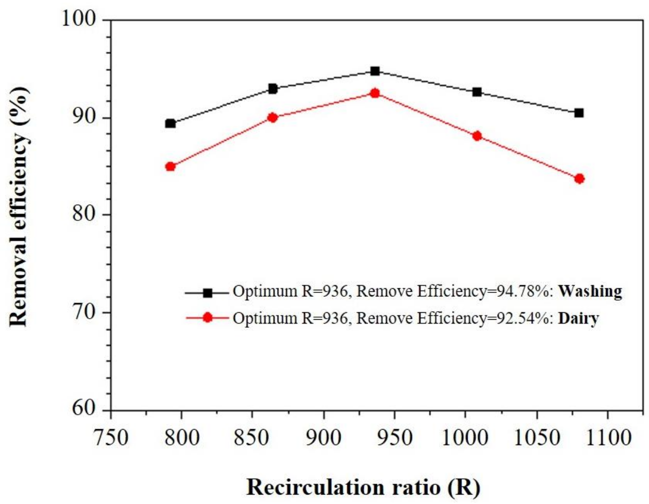

Figure 5 Relationship between removal efficiency and recirculation ratio (R)

The correlation coefficient, R^2 was used to select the best kinetic models.

2.3.3 Experimental set-up of FBBR- GAC

A FBBR- GAC was designed and constructed using a 12.2 L acrylic cylinder with height 1 m and a 0.0165 m^2 cross-sectional area (AR) as shown in Figure 4. The fluid flowed in an upward spiral direction toward a 20 L wastewater tank. It was found that optimal conditions were 4 kg of dry weight GAC, an initial height of bed (h_0) 0.55 m, and flow rate of recirculation at five levels:(Q_{Re} =11, 12, 13, 14, and 15 L/min with corresponding height of water levels of (h_{Water}) at 0.725, 0.73, 0.735, 0.74, 0.745, 0.75 m, respectively. From Eq. (1), the percent of distribution of the bed (D.B.%) was 89.04, 89.80, 90.54, 91.28, and 92.00, respectively. The bed's stirrer speed (N_B) in Eq. (2) was 19, 22, 25, 28, and 31 rpm, respectively [4]. The experimental hydraulic recirculation time (HReT, t_{Re}) was set at seven levels, 10, 20, 30, 60, 90, 120 and 150 min. The results of the experiment were analyzed and compared with the predictions of the two developed mathematical models, Eq. (18) and (32), for the RPFR and RCSTR, respectively. This was done using the rate coefficient, k to determine which model is the most accurate.

3. Results and discussion

3.1 Effect of optimum recirculation ration (R) to the COD removal efficiency

This study developed two mathematical models: for a recirculation plug-flow reactor (RPFR) and a recirculation completely-mixed stirred tank reactor (RCSTR). This was done to predict the performance of a fluidized bed bioreactor using granular activated carbon (FBBR-GAC). Table 2 illustrates the quality of water after treatment in a FBBR-GAC reactor over time in terms of its organic loading rate. Both models, RPFR and RCSTR, were used to predict the COD in the effluent using the fitted kinetic rate constants (k). It was shown that optimum recirculation ratio (R) was 936 and optimum rate stirrer speed (NB) was 25 rpm, resulting in the highest adsorption-biodegradation capacity in a FBBR-GAC process in terms of chemical oxygen demand (COD) removal. Bioreactor treatment efficiency depended on the hydraulic recirculation time (HReT), 150 min or 0.104 days as shown in Figure 5.

3.2 Kinetic studies of COD removal using a FBBR-GAC

Though both models can predict the performance of a FBBR-GAC, this study aimed to develop mathematical models and identified which one among them is the most accurate. From Table 3, R^2 values indicate that the kinetics of COD reduction followed a pseudo 2nd order reaction, as demonstrated in Figure 6.

Table 2 The quality of wastewater at various recirculation ratios (R) in terms of organic loading rate

WW	Q_{Re}	Qin	COD_{in}	OLR	HRT	R	DB	N_B	COD(mg/L)						
									Reaction time (min)						
	(L/m)	(L/d)	(mg/L)	kgCOD$_{in}$/ m3 day	day	(Q_{Re}/Q_{in})	%	rpm	10	20	30	60	90	120	150
	11	20	2939	23.066	0.127	792	88.8	19	1412.54	1119.6	994.21	615.92	494.75	404.14	311.41
	12	20	2839	21.582	0.132	864	89.4	22	1262.69	979.72	858.6	493.17	376.12	262.63	199.02
Washing	**13**	**20**	**2789**	**20.557**	**0.136**	**936**	**89.9**	**25**	**1190.46**	**912.47**	**793.48**	**434.49**	**319.5**	**164.51**	**145.52**
	14	20	2849	20.380	0.140	1008	90.4	28	1277.36	993.39	871.84	505.13	387.66	248.34	209.94
	15	20	2909	20.212	0.144	1080	90.9	31	1366.83	1076.89	952.78	578.34	458.41	365.95	276.94
	11	20	4289	33.661	0.127	792	88.8	19	2234.76	1806.84	1635.89	1110.13	898.33	667.17	642.45
	12	20	4089	31.084	0.132	864	89.4	22	1925.55	1517.58	1354.6	853.36	651.43	431.05	407.48
Dairy	**13**	**20**	**3989**	**29.402**	**0.136**	**936**	**89.9**	**25**	**1778.46**	**1380.47**	**1221.48**	**732.49**	**535.5**	**320.51**	**297.52**
	14	20	4164	29.786	0.140	1008	90.4	28	2039.15	1623.7	1457.74	947.3	741.67	517.25	493.25
	15	20	4339	30.148	0.144	1080	90.9	31	2315.19	1882.29	1709.35	1177.46	963.19	729.33	704.33

Table 3 Kinetics of 1st order and 2nd order models

Waste water	Models	Rate constant, k ($mg^{-1} Ld^{-1}$)	R^2
Washing	1st order	0.302 x10^2	0.8706
	2nd order	4.685 x10^{-2}	0.9944
Dairy	1st order	0.275 x10^2	0.8613
	2nd order	2.811 x10^{-2}	0.9922

*For a HRT = 0.136 days and a recirculation ratio, R = 936 gives the highest COD removal efficiency.

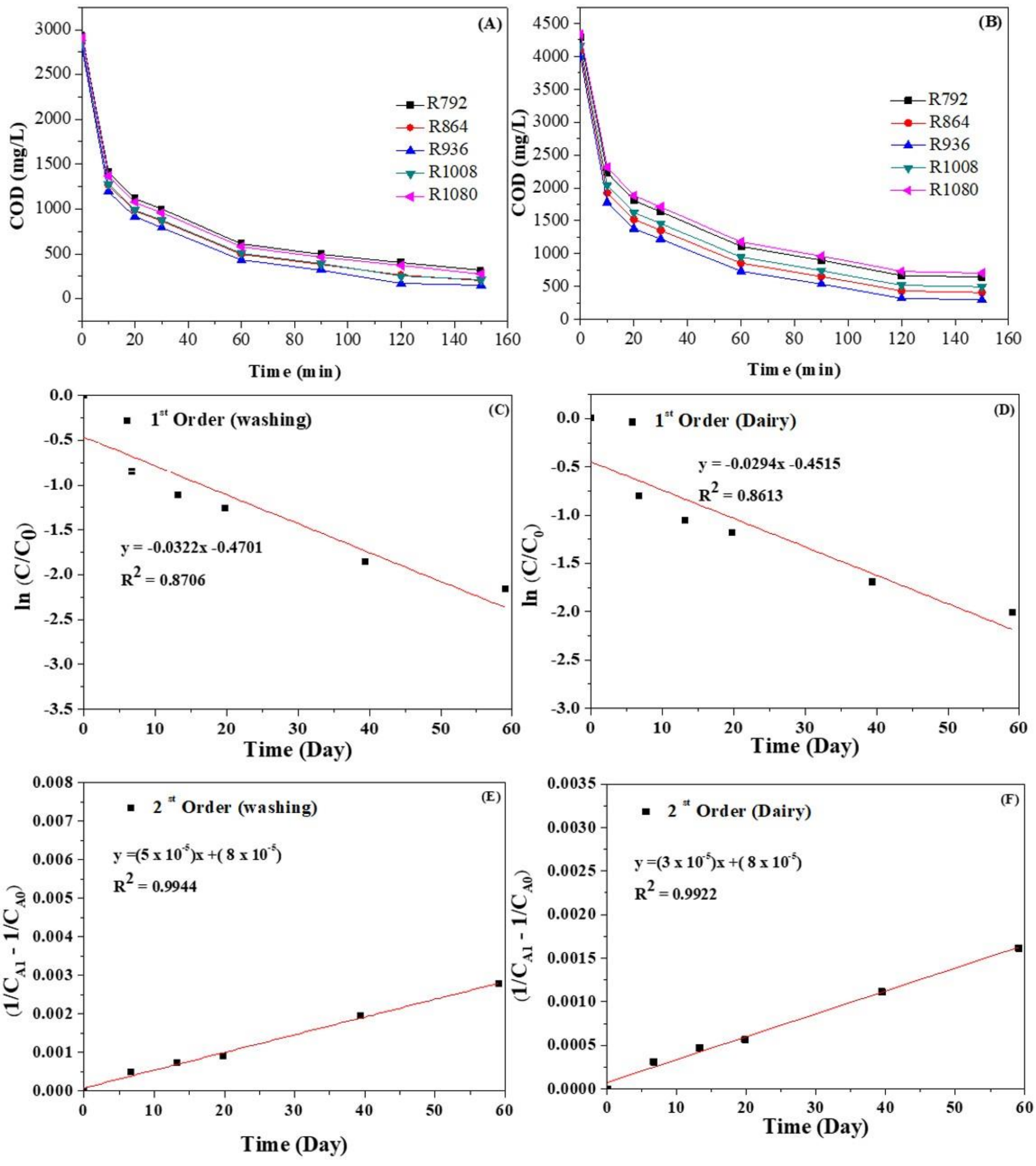

Figure 6 Prediction of kinetic reactions using 1st order and 2nd order models, (B) kinetic study of COD reduction from washing wastewater, (C) kinetic study of COD reduction from dairy wastewater

3.3 Reactor modelling of FBBR- GAC

The optimum recirculation (R) and kinetic rate coefficient, (k) were used to determine the performance of FBBR- GAC's COD removal to identify which model is the most accurate. Actual results for treated wastewater were compared to the predictions of Eq. (21) for a RPFR and Eq. (36) for a RCSTR:

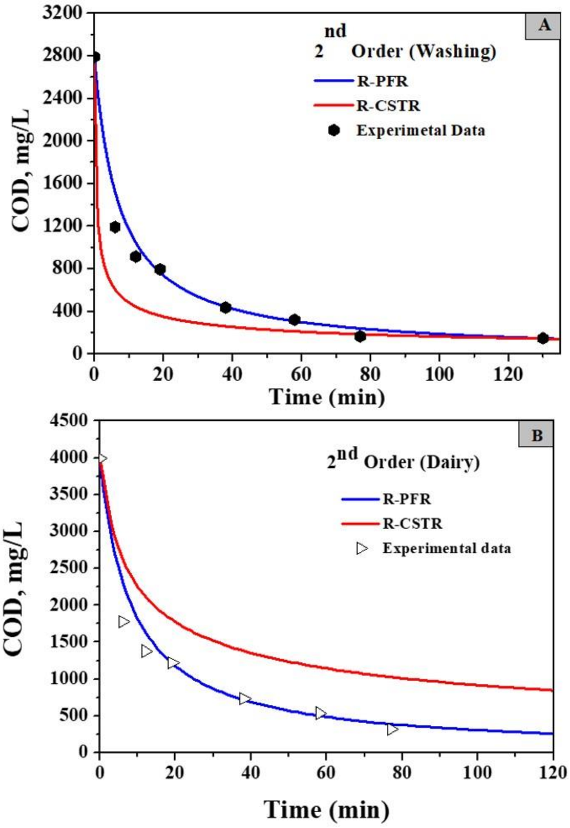

Figure 7 Comparison of RPFR and RCSTR models (HRT=0.136 days and R=936)

This present study used MS Excel for mathematical simulation of the RPFR and RCSTR models derived in Section 2.2. Figure 7 illustrate the predicted behavior of the RPFR and RCSTR reactors. It was found that the experimental data fitted the RPFR model better than the RCSTR model.

4. Conclusions

From the experimental data, it was found that the highest COD removal (>92%) was achieved at an optimum recirculation ratio (R) of 936 with a bed stirrer speed (N_B) of 25 rpm. The reaction kinetics for COD removal using washing and dairy wastewater followed the 2nd order kinetic models, with kinetic rate constants (k) of 4.68 x10^{-2} and 2.81 x10^{-2} mg^{-1} Ld^{-1}, for the RPFR and RCSTR, respectively. Optimal recirculation RPFR and RCSTR for first and second order were successfully derived and validated with experimental data for both wastewater types. These models were developed to evaluate the kinetics of adsorption-biodegradation of chemical oxygen demand (COD) onto a granular activated carbon during a treatment processes. The results of the study showed that these RPFR models can predict the COD effluent precisely and can be further applied to predict the performance of this type of reactor with other types of wastewater.

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