แบบจำลองทางคณิตศาสตร์ของระบบบึงประดิษฐ์การไหลเวียนใต้ชั้นกรองในการบำบัดน้ำเสียชุมชนสำหรับที่พักอาศัย

Mathematical Model of Subsurface Recirculation Flow Constructed Wetland Domestic Wastewater Treatment for Household

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บทคัดย่อ

จากการพัฒนาแบบจำลองแบบพลวัตเครื่องปฏิกรณ์ปลั๊กไหลแบบหมุนเวียน (Recirculation plug-flow reactor :RPFR) ของระบบบำบัดน้ำเสียบึงประดิษฐ์การไหลเวียนใต้ชั้นกรอง (Recirculation surface flow constructed wetland: RSFCW) ใช้ตัวกลางขยะรีไซเคิลพลาสติกบรรจุในถังโพลีเอสเตอร์สจำนวน 3 ถัง มีอัตราส่วนความกว้าง:ความยาว (>1:4) ใช้พื้นที่ปลูกต้นกก (Ap) 1.98 ตร.ม.ความลึกชั้นกรองที่ 25 ซม. อัตราส่วนการหมุนเวียน (Recirculation ratio : Q_{Re}/Q_{in}) R=0.85 และเวลากักเก็บหมุนเวียน (Hydraulic recirculation time: HReT) 12 ชั่วโมงในการบำบัดน้ำเสียชุมชนพบว่ามีประสิทธิภาพการกำจัดค่าบีโอดี (Removal BOD efficiency) 81.04% เกิดปฏิกิริยาอันดับ 2 มีค่าสัมประสิทธิ์ของการย่อยสลาย K_2nd_{RPFR} เท่ากับ 0.011 day^{-1} ซึ่งถือได้ว่าเป็นระบบบำบัดอีกทางเลือกที่น่าสนใจสำหรับพักอาศัยในการปลุกจิตใต้สำนึกสำหรับลดภาระทางเทศบาลที่จะต้องจัดสรรงบรัฐบาลในการกำจัดน้ำเสียและขยะพลาสติก

คำสำคัญ: แบบจำลองทางคณิตศาสตร์ ระบบบึงประดิษฐ์การไหลเวียนใต้ชั้นกรอง การบำบัดน้ำเสียชุมชนสำหรับที่พักอาศัย

Abstract

According to the dynamic model of the recirculation plug-flow reactor (RPFR) of subsurface recirculation flow constructed wetland (SRFCW) by using the recycled plastic media contained inside the three polyester tanks with the ratio of Width: length equals > 1: 4. The area of planting reed (Ap) was 1.98 square meters. The depth of subsurface was 25 cm. The recirculation ratio (Q_{Re}/Q_{in}), R, was 0.85, with hydraulic recirculation time (HReT) of 12 hours for treating domestic wastewater. The results showed that the BOD removal efficiency was 81.04% and produced the second-order-reaction with a coefficient of constant K_2nd_{RPFR} equals 0.011 day^{-1} which was the interesting alternative treatment for households to instill conscience which helps to reduce the responsibility of the municipality in allocating the government funds to eliminate wastewater and plastic waste.

Keywords: Mathematical model, Subsurface recirculation flow constructed wetland, Domestic wastewater treatment for household

Introduction

Municipal wastewater and waste are contaminated with organic matter, inorganic matter, and microorganisms from excretions which make them disgusting and harmful to health and sanitation (Pollution Control Department, 2012; Pollution Control Department, 2016). A constructed wetland is the system that uses a natural process which appropriates (Haddaji, 2019) to the general conditions of local. Using the benefit of plastic recycled waste from households (Jeamponk, 2012) as subsurface of constructed wetland is the interesting method in the present to reduce waste (Sittiritkawin et al., 2019) and impurities of wastewater or BOD to level at standard (Suksomboon & Junsiri, 2018; Suksomboon et al., 2019a; Suksomboon et al., 2019b). It should be a suitable wastewater treatment system for the community.

A constructed wetland is a system suitable for the local conditions of the community in Thailand based on the appropriate weather that is the tropical country. Currently, the government has the policy to support locals to construct a small constructed wetland rather than constructing a large integrated system (Suksomboon, 2007). Therefore the recirculation surface flow constructed wetland (RSFCW) is an interesting treatment since it uses less space from households but high efficiency to remove BOD of community wastewater by transferring sufficient oxygen to bacteria and using air to decompose organic matter (Nivala, 2013) without producing odor and carrier. However, SRFCW still has a problem with subsurface clogging (Gross, 2007) which leads to the concept to develop SRFCW by using recycled plastic waste as a medium to increase the space of subsurface and reduce the amount of waste from the household. The waste rate is in the range of 0.3-1.44 kg/person/day: most of it was an organic waste (48%), followed with paper (15 %), plastic (14%), glass (5%), metals (4%), and so on, respectively (Kaosol, 2009). To increase BOD removal efficiency of domestic wastewater, recirculation ratio (Q_{Re}/Q_{in}= R) (Xing et al., 2010; Suksomboon & Junsiri, 2018; Suksomboon et al., 2019a; Suksomboon et al., 2019b), hydraulic recirculation time (HReT), background concentration (C*) (Kadlec & Wallace, 2009), and Area of Plant (Ap) were used to develop a mathematical model for determining the coefficient of constant (k).

The objectives of this study were to determine BOD removal efficiency and to develop a recirculation plug-flow reactor (RPFR) of SRFCW's first-order reaction and second-order reaction (n = 1 and n = 2) for determining the optimal value of the coefficient of constant and examining the accuracy from development the mathematical model.

Methodology

Research procedures were as follows:

1. Recycled waste media

Buying all kinds of plastic bags, then tied them into toffee shape. Plastic water bottles were cut into four ratios, 1:1, using as subsurface contained inside the three polyester tanks. The area of planting reed (area of plant) was 1.98 square meters with a ratio of Width: length equals > 1: 4 – the total area was 1.98 square meters and the depth of subsurface was 25 cm (Nivala, 2013). The density (F) inside the constructed wetland planting reeds was 0.46 and was covered by the stones size 3/4 inch for preventing floating.

2. Wastewater

According to the results of the study of activities causing the domestic wastewater found that three activities of each household causing the wastewater the most which were 1) showering or bathing: average 26.47 liters/day/person, 2) washing: average 19.73 liters/day/person, and 3) toilet: average 15.85 liters/day/person, respectively (Jeamponk, 2012). The wastewater was contained in the tanks for fifteen days to reduce the concentration of organic matter (Pollution Control Department, 2012) and the water impurities in the range of 80–110 mg/l (Kadlec & Wallace, 2009).

3. Development the dynamic model of reactor

To develop the mathematical model of constructed wetland that has the highest efficiency to remove BOD must consider both first-order-reaction and second-order-reaction (n = 1 and n = 2) of the RPFR model because this treatment, RPFR, uses a narrow area with a ratio of width: length equals >1:4 (Nivala, 2013; Suksomboon et al., 2019a; Suksomboon et al., 2019b). To model the behavior of RPFR's dynamic model, the background concentration (C*) (Kadlec & Wallace, 2009) from mass balance was added to illustrate the elimination of the following elements in the wetlands.

3.1 Development Recirculation Plug-flow reactor (RPFR)

The recirculation plug-flow reactor operates in a steady-stat

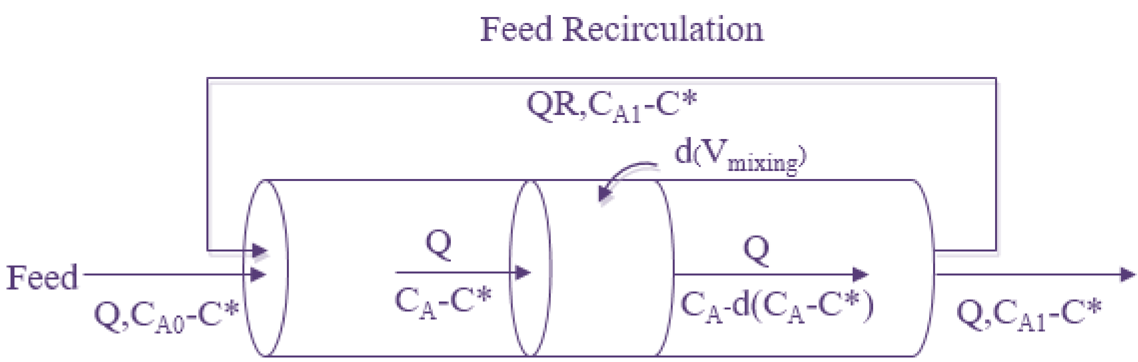

Figure 1 Development Recirculation Plug-flow Reactor (RPFR)
(Source: Rattapol Suksomboon et al., 2020)

To develop the ideal plug – flow reactor (IPFR) into RPFR and has the characteristics like a piston model as shown in Figure 1. The component A specified feed flow rate and recirculation feed flow rate (Q+QR) (Suksomboon & Junsiri, 2018; Suksomboon et al., 2019a; Suksomboon et al., 2019b), and specified the influent was C_{A0}-C* and the effluent was C_{A1}-C* (Kadlec & Wallace, 2009) which make the mass travel to the starting point of concentration in perpendicular direction. The flow decreased evenly throughout the piston in mixing volume (V_{mixing}) which can be written in a partial differential equation. It illustrated the change of concentration per unit of recirculation ratio (Q_{Re}/Q_{in}= R) (Xing wen et al., 2010; Suksomboon & Junsiri, 2018; Suksomboon et al., 2019a; Suksomboon et al., 2019b), hydraulic recirculation time (HReT), BOD background concentration (BOD*), and area of plant (Ap) of a constructed wetland of each component of the volume of flow direction as followed:

Considering the first-order-reaction (n=1)

$$(Q+QR)(C_A-C^*)=(Q+QR)((C_A-C^*)-d(C_A-C^*))+r_A d(V_{mixing}) \quad (1)$$

Reaction rate is $r_A=-k_1 st_{RPFR}(C_A-C^*)$ can be written in equation as follows:

$$(Q+QR)(C_A-C^*)=(Q+QR)((C_A-C^*)-d(C_A-C^*))-k_1 st_{RPFR}(C_A-C^*)d(V_{mixing}) \quad (2)$$

Given Recirculation ratio as Q_{Re}/Q_{in}= R

$$(Q+QR)d(C_A-C^*)=-k_1 st_{RPFR}(C_A-C^*)d(V_{mixing}) \quad (3)$$

Integration yields

$$\int_{C_{A0}}^{C_{A1}}\frac{d(C_A-C^*)}{(C_A-C^*)}=\frac{-k_1 st_{RPFR}}{(Q+QR)}\int_0^{V_{mixing}}d(V_{mixing}) \quad (4)$$

$$\ln\left(\frac{(C_{A1}-C^*)}{(C_{A0}-C^*)}\right)=-k_1 st_{RPFR}\frac{V_{mixing}}{(Q+QR)} \quad (5)$$

From $V_{mixing}=V_r+V_{re}$ Volume of mixing; V_r= Mass volume of reactor and V_{Re}= Recirculation mass volume of reactor

$$\ln\left(\frac{(C_{A1}-C^*)}{(C_{A0}-C^*)}\right)=-k_1 st_{RPFR}\frac{V_r+V_{Re}}{(Q+QR)} \quad (6)$$

Given $V_r=Qt_{PFR};t_{PFR}$ and $V_{re}=QRt_{Re};t_{Re}$

$$\ln\left(\frac{(C_{A1}-C^*)}{(C_{A0}-C^*)}\right)=-k_1 st_{RPFR}\frac{(Qt_{PFR}+QRt_{Re})}{(Q+QR)} \quad (7)$$

To

$$\ln\left(\frac{(C_{A1}-C^*)}{(C_{A0}-C^*)}\right)=-k_1 st_{RPFR}\frac{(t_{PFR}+Rt_{Re})}{(1+R)} \quad (8)$$

Given $t_{PFR}=\frac{V_r}{Q}=\frac{(1-F)A_P h}{Q}$; F = Density of media and h = height of Water replacing in Equation 8 to find the coefficient of constant ($k_1 st_{RPFR}$) by slope

$$k_1 st_{RPFR}=-\frac{\ln\left(\frac{C_{A1}-C^*}{C_{A0}-C^*}\right)}{\frac{\left(\frac{(1-F)A_P h}{Q}+Rt_{Re}\right)}{(1+R)}} \quad (9)$$

Therefore the solving equation of the concentration of RPFR's the first-order-reaction (n=1) is

$$C_{A1}=C^*+(C_{A0}-C^*)e^{-k_1 st_{RPFR}\frac{\left(\frac{(1-F)A_P h}{Q}+Rt_{Re}\right)}{(1+R)}} \quad (10)$$

Considering the second-order-reaction (n=2)

$$(Q+QR)d(C_A - C^*) = r_A d(V_{mixing}) \tag{11}$$

Reaction rate is $r_A = -k_2 nd_{RPFR}(C_A - C^*)^2$ can be written in equation as follows:

$$(Q+QR)d(C_A - C^*) = -k_2 nd_{RPFR}(C_A - C^*)^2 d(V_{mixing}) \tag{12}$$

Integration yields

$$\int_{C_{A0}-C^*}^{C_{A1}-C^*} \frac{d(C_A - C^*)}{(C_A - C^*)^2} = \frac{-k_2 nd_{RPFR}}{Q+QR} \int_0^{Vmixing} d(V_{mixing}) \tag{13}$$

$$\frac{1}{C_{A0}-C^*} - \frac{1}{C_{A1}-C^*} = -k_2 nd_{RPFR}\left(\frac{V_{mixing}}{Q+QR}\right) \tag{14}$$

To

$$\frac{1}{C_{A0}-C^*} - \frac{1}{C_{A1}-C^*} = -k_2 nd_{RPFR}\left(\frac{V_r + V_{\mathrm{Re}}}{Q+QR}\right) \tag{15}$$

Given $V_r = Qt_{PFR}; t_{PFR}$ and $V_{re} = QRt_{\mathrm{Re}}; t_{\mathrm{Re}}$

$$\frac{1}{C_{A0}-C^*} - \frac{1}{C_{A1}-C^*} = -k_2 nd_{RPFR}\left(\frac{Qt_{PFR} + QRt_{\mathrm{Re}}}{Q+QR}\right) \tag{16}$$

To

$$\frac{1}{C_{A0}-C^*} - \frac{1}{C_{A1}-C^*} = -k_2 nd_{RPFR}\left(\frac{t_{PFR} + Rt_{\mathrm{Re}}}{1+R}\right) \tag{17}$$

Equation 17 to find the coefficient of constant (k_2nd_{RPFR}) by slope

$$k_2 nd_{RPFR} = \frac{\left(\frac{1}{C_{A1}-C^*} - \frac{1}{C_{A0}-C^*}\right)}{\frac{\frac{(1-f)A_p h}{Q} + Rt_{\mathrm{Re}}}{1+R}} \tag{18}$$

Therefore the solving equation of the concentration of RPFR's the second-order-reaction (n=2) is as following

$$C_{A1} = C^* + \frac{(C_{A0} - C^*)}{\left(1 + (C_{A0} - C^*)k_2 nd_{RPFR}\left(\frac{\frac{(1-f)A_p h}{Q} + Rt_{\mathrm{Re}}}{1+R}\right)\right)} \tag{19}$$

3. Experimental setup

To experiment the RSFCW using recirculation ratio (Q_{Re}/Q_{in}), R= 0.85, of fluidized bed bioreactor (Xing et al., 2012) by turning on the feeding pump with Q_{in} of wastewater of 63 liters per day per person, and turning on recirculation pump with Q_{Re} of 54 liters per day per person using HReT at 4, 8, and 12 hours for treatment (Haddaji, 2019). Examining the quality of water of constructed wetland, BOD, by collecting the sample water from four points as shown in Figure 2 according to Standard Method (APHA et al., 1999) to find BOD removal efficiency. The conducted data were recorded in Microsoft Excel in order to calibrate the optimal coefficient of constant (k) from Equation 9 and 18 and to examine the accuracy with Equation 10 and 19.

Figure 2 Subsurface Recirculation Flow Constructed Wetland (SRFCW)
(Source: Rattapol Suksomboon et al., 2020)

Results

The results of the study of subsurface recirculation flow constructed wetland (SRFCW) for households consisted of toffee shape recycled plastic media (Jeamponk, 2012) and plastic water bottles cut into four ratios, 1:1, to increase the space of subsurface contained inside the three polyester tanks with a ratio of Width: length (> 1: 4). The area of planting umbrella reed (Ap) was 1.98 square meters, the depth of subsurface was 25 cm (Nivala, 2013), and the density of reeds (F) was 0.46 (Suksomboon, 2007). Using recirculation ratio (QRe/Qin), R= 0.85, of fluidized bed bioreactor (Xing et al., 2012) by turning on the feeding pump with Qin of wastewater of 63 liters per day per person, QRe of 54 liters per day per person, and HReT at 4, 8, and 12 hours (Haddaji, 2019), the results revealed that the BOD removal efficiency was 62.74%, 75.53%, and 81.04% as shown in Figure 3 and Table 1.

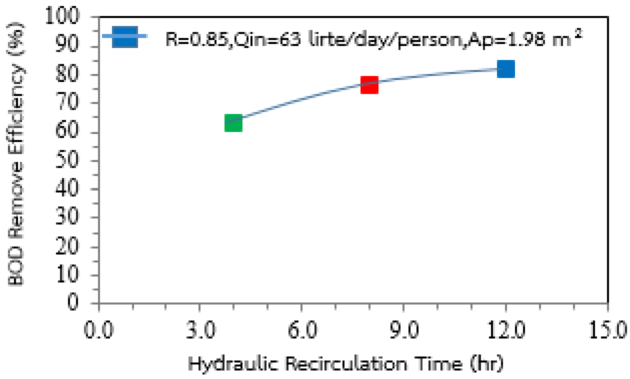

Figure 3 The correlation between BOD Removal Efficiency and HReT

According to the highest BOD removal efficiency from developing recirculation plug-flow reactor (RPFR) found that subsurface recirculation flow constructed wetland (SRFCW) from Equation 8 and 17 producing the first-order-reaction and the second-order-reaction, the coefficient of constant was K_1st_{RPFR} and K_2nd_{RPFR} equaling 0.231 day^{-1} and 0.011 day^{-1} as shown in Table 2 and Figure 4.

Table 1 BOD Removal Efficiency and hydraulic recirculation time (HReT)

Ap m^2	H m	1-F	Q_{in} m^3/d	Q_{Re} m^3/d	R	HReT hr	BOD* mg/l	BOD mg/l	BOD Removal Efficiency %
								97.50	0
0.66	0.25	0.54	0.63	0,54	0.85	4	5	37.55	62.74
1.32	0.25	0.54	0.63	0,54	0.85	8	5	24.75	75.53
1.98	0.25	0.54	0.63	0,54	0.85	12	5	19.18	81.04

BOD* = 5 mg/l (Kadlec & Wallace, 2009)

Table 2 Calibration of dynamic model of recirculation plug-flow reactor (RPFR): the first-order-reaction and the second-order-reaction

Reactor	Try	Models	Rate constant, k (day^{-1})	r^2
RSFCW	RPFR	1st order	0.231	0.94
	RPFR	2nd order	0.011	0.98

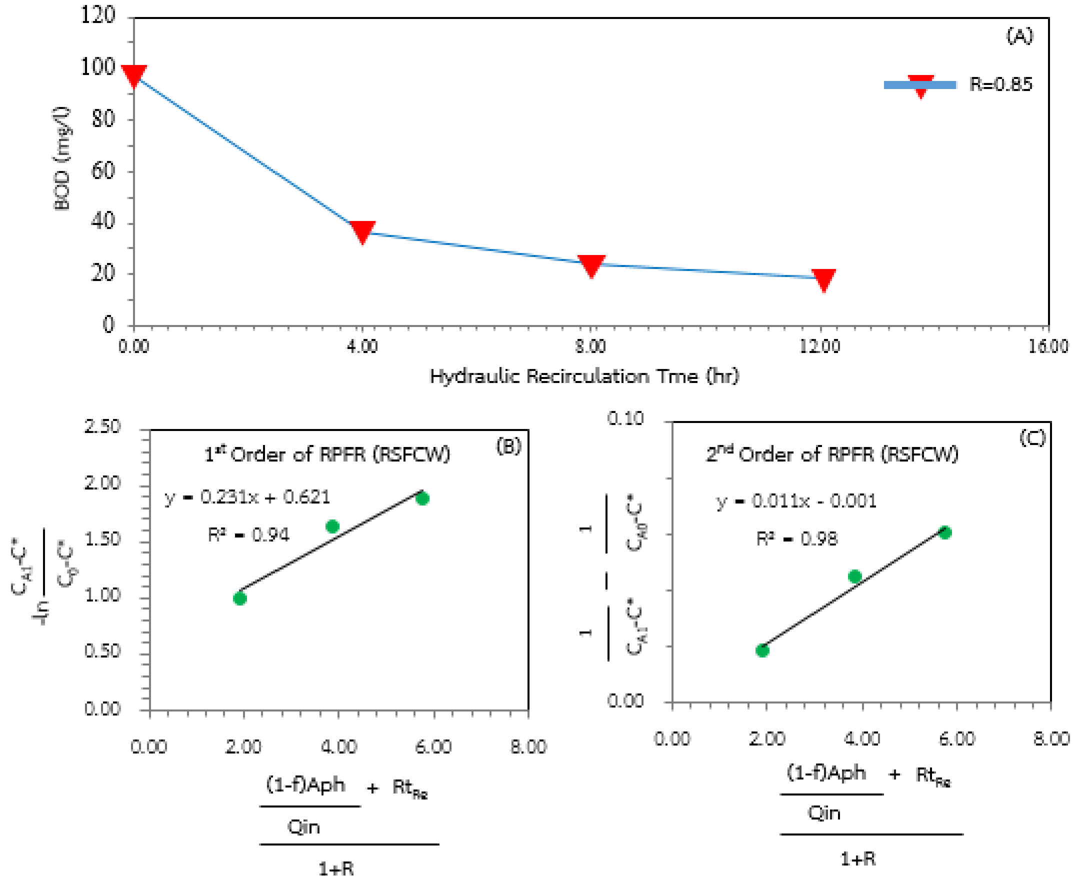

Figure 4 The prediction of RPFR model: the first-order-reaction and the second-order-reaction of SRFCW; BOD dynamic model of community wastewater: (a), (B), (C)

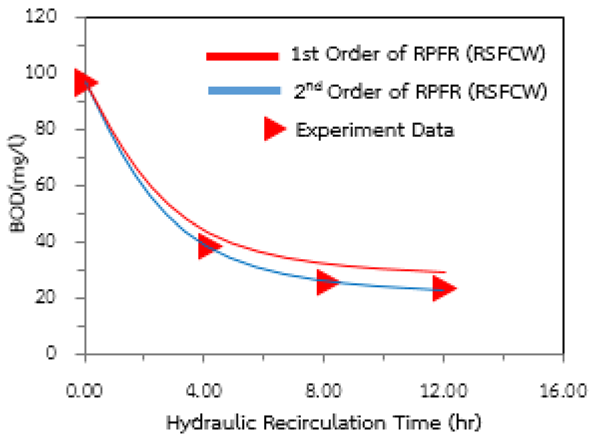

Figure 5 Calibration of recirculation plug-flow reactor (RPFR): the first-order-reaction and the second-order-reaction

Discussion

Developing the dynamic model of recirculation plug-flow reactor (RPFR) of subsurface recirculation flow constructed wetland (SRFCW) by using the recycled plastic media contained inside the three polyester tanks with a ratio of Width: length equals > 1: 4. The area of planting reed (Ap) was 1.98 square meters. The depth of subsurface was 25 cm. The recirculation ratio (QRe/Qin), R, of 0.85 with Qin of wastewater of 63 liters per day per person, QRe of 54 liters per day per person, and HReT of 12 hours, the BOD removal efficiency was 81.04%. The development of the mathematical model of RPFR's dynamic model found that the subsurface recirculation flow constructed wetland (SRFCW) produced the second-order-reaction with a coefficient of constant K_2nd_{RPFR} equals 0.011 $day^{-1.}$

Conclusion and Suggestions

The development of the dynamic model of the recirculation plug-flow reactor (RPFR) of SRFCW produced the first-order-reaction and the second-order-reaction, r^2 equal 0.94 and 0.98 – which were the insignificant difference. The number of bacteria increased inside the subsurface. The growth of plant roots made the space of subsurface more narrow. Therefore, the subsurface cleaning system should be installed for preventing clogging when the reactor was used for a long time. The coefficient of flow inside the subsurface should be studied in order to design the subsurface recirculation flow constructed wetland (SRFCW).

New knowledge and the effects on society local and communities

The subsurface recirculation flow constructed wetland (SRFCW) in households can eliminate the wastewater, reduce the amount of plastic waste, and increase the green area. SRFCW is easy to build and saving – local people can build it by themselves. Therefore, it is an interesting alternative way for every household to instill conscience which helps to reduce the responsibility of the municipality in allocating the government funds to eliminate wastewater and plastic waste.

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