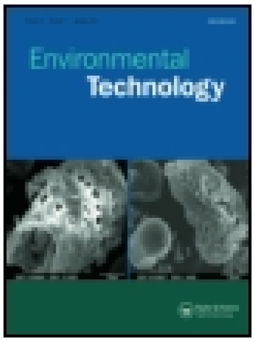

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Multi-stage hybrid subsurface flow constructed wetlands for treating piggery and dairy wastewater in cold climate

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ABSTRACT

This study followed three field-scale hybrid subsurface flow constructed wetland (CW) systems constructed in Hokkaido, northern Japan: piggery O (2009), dairy G (2011), and dairy S (2006). Treatment performance was monitored from the outset of operation for each CW. The ranges of overall purification efficiency for these systems were 70–86%, 40–85%, 71–90%, 91–96%, 94–98%, 84–97%, and 70–97% for total N (TN), NH_4-N, total P, chemical oxygen demand (COD), biochemical oxygen demand, suspended solid, and total Coliform, respectively. The hybrid system's removal rates were highest when influent loads were high. COD removal rates were 46.4 ± 49.2, 94.1 ± 36.6, and 25.1 ± 15.5 g COD m^{-2} d^{-1} in piggery O, dairy G, and dairy S, with average influent loads of 50.5 ± 51.5, 98.9 ± 37.1, and 26.9 ± 16.0 g COD m^{-2} d^{-1}, respectively. The systems had overall COD removal efficiencies of around 90%. TN removal efficiencies were 62 ± 19%, 82 ± 9%, and 82 ± 15% in piggery O, dairy G, and dairy S, respectively. NH_4-N removal efficiency was adversely affected by the COD/TN ratio. Results from this study prove that these treatment systems have sustained and positive pollutant removal efficiencies, which were achieved even under extremely cold climate conditions and many years after initial construction.

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1. Introduction

Hybrid subsurface flow constructed wetlands (CWs) are widely used to treat wastewater. Typically, they feature subsurface horizontal flow (HF) and subsurface vertical flow (VF) in a series to achieve higher treatment effect. VF can provide a good condition for nitrification but HF cannot do this because of the limited oxygen transfer capacity, while HF is highly effective in denitrification.[1,2] Overall, hybrid subsurface flow CW advantages include low cost, low energy consumption, low maintenance requirement, and environmental friendliness.[3]

In recent decades, there have been a number of studies regarding high content of wastewater, such as piggery urine and dairy parlor discharge. Cronk [4] studied CW treatment of wastewater from dairy and swine operations and found that surface flow wetlands were most common. Shamir et al. [5] used surface flow CWs to treat dairy wastewater. Kantawanichkul and Somprasert [6] studied the efficiency of a pig farm wastewater treatment CW, featuring VF above HF. There have also been studies regarding CW performance for treatment of livestock and dairy farms' wastewater.[7–12] Among the studied high content wastewater treatment systems, most were not hybrid subsurface flow CWs. Some hybrid systems have been evaluated, but many of those studied have been in a pilot phase or built to an experimental scale. There are limited data regarding field-scale hybrid subsurface flow CW systems. Moreover, there are even lesser data regarding long-term hybrid subsurface flow CW performance.

In order to better understand hybrid subsurface flow CW performance, there have been some studies regarding the influence of environmental factors upon treatment efficiency. One study reported that nitrification was dependent on temperature; the researchers found favorable conditions for nitrification between 16.5°C and 32°C, and unfavorable conditions at lower temperatures.[3] Mietto et al. [13] also reported that temperature affected N removal in a hybrid system. Further, low availability of organic carbon has been shown to restrict the microbiological N removal because denitrification requires organic feedstock.[3] There are a number of studies regarding the addition of carbon from external sources.[14–17] Another known problem related to conventional biological N removal is the limited supply of dissolved oxygen (DO), for which nitrifying bacteria must compete with organics.[18] Artificial aeration

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could significantly improve oxygenation for nitrification in hybrid subsurface flow CWs.[19]

As of 2014, there were 246 piggery farms and 6900 dairy farms in Hokkaido, Japan (Ministry of Agriculture, Forestry, and Fisheries, Japan). These farms produce high content wastewater, which must be effectively treated to prevent environmental problems. This study analyzed urine wastewater from a piggery farm with 1000 mg total N (TN) L^{-1}, and milking parlor wastewater from two dairy farms with chemical oxygen demand (COD) of 3000–10,000 mg L^{-1}. The studied farms use hybrid subsurface flow CWs to treat wastewater.

The objective of this study was to evaluate pollutant treatment efficiency in three hybrid subsurface flow CWs over several years of operation. The study also evaluated environmental parameters, as they relate to pollutant removal efficiency (RE). This study built upon the previous research reported by Kato et al. [20,21] and Sharma et al.[22,23]

2. Materials and methods

2.1. Study site

The hybrid subsurface flow CW system treating livestock wastewater from O piggery farm is located in Chitose (piggery O, N42°49′, E141°44′), the system treating milking parlor wastewater from G dairy farm is located in Takinoue (dairy G, N44°8′, E143°2′), and the system treating milking parlor wastewater from S dairy farm is located in Embetsu (dairy S, N44°45′, E141°48′), Hokkaido, Japan (Figure 1). Table 1 shows information regarding these three hybrid systems, including location, average air temperature, average precipitation, construction year, and assessment period. The assessment period started at each system's commencement of operation and finished in December 2014. Average maximum air temperatures were 30.9 ± 1.8°C, 33.5 ± 1.0°C, and 30.0 ± 1.4°C and average minimum air temperatures were −23.4 ± 1.3°C, −29.6 ± 0.7°C, and −21.1 ± 2.3°C for piggery O, dairy G, and dairy S, respectively. Local meteorological data were provided by AMeDAS of Japan Meteorological Agency.

2.2. System outline

Each hybrid subsurface flow CW system featured 2–4 VFs and one HF in a series. Figure 2 shows a schematic diagram of a hybrid subsurface flow CW of piggery O as an example.[24] Table 2 shows construction details for each system, and piggery O is discussed below as an example.

Piggery O was constructed with four VFs (V), a single HF (H), and a special lagoon reservoir. Each V was equipped with a self-priming siphon.[20,21] After piggery urine was separated, the liquid was dosed into the hybrid system but part of the effluent from the 3rd V was pumped into the 1st Vr and 2nd Vr (Vr refers to the V bed with recirculation) in order to improve total performance. The surface of the 1st Vr was divided into three zones while the 2nd Vr and 3rd V were divided into two zones; these zones could be used alternately to maintain dry conditions like in a French system.[25] Dairy G was constructed with Vr-V-V-H-V in series, while dairy S was constructed with V-Vr-H in

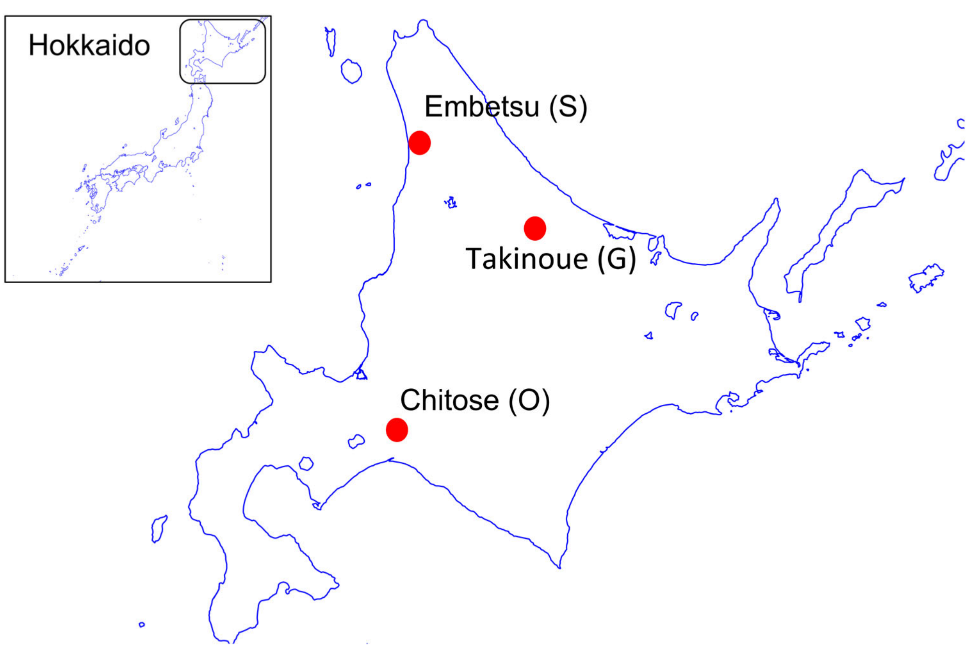

Figure 1. Location of three hybrid subsurface flow CW systems in Hokkaido, Japan.

Table 1. Precipitation, temperature, construction year of the hybrid subsurface flow CWs, and assessment period. Average values represent mean ± standard deviation.

System name	Location	Average precipitation (mm y^{-1})	Average air temperature (°C)	Construction year	Assessment period
Piggery O	Chitose	1029 ± 85	7.3 ± 0.3	2009	Dec. 2009–Dec. 2014
Dairy G	Takinoue	1053 ± 81	5.2 ± 0.2	2011	May 2011–Dec. 2014
Dairy S	Embetsu	1150 ± 192	6.9 ± 0.3	2006	Nov. 2006–Dec. 2014

series. Total areas of piggery O, dairy G, and dairy S were 1472, 3048, and 656 m^2, respectively. Piggery O used volcanic porous pumice gravel for the main bed material, dairy G used sand, and dairy S used a combination of sand, river gravel, and clinker ash. Common reed (*Phragmites australis*) was the main vegetation planted in the hybrid system and it was not harvested.

2.3. Hydraulic load

Piggery O's average hydraulic loading rate was 0.7 cm d^{-1}; the recirculation frequency from the 3rd V into the 1st Vr was once every 3 h and lasted for 30 min each, while it was same frequency from the 3rd V into the 2nd Vr but lasted for 90 min for each pumping. The recirculation rate of effluent pumped from the 3rd V into the 1st Vr was 230% and it was 60% in the 2nd Vr. Dairy G's average hydraulic loading rate was 1.0 cm d^{-1}, while the recirculation scheduled was only for 15 min once a day, with a recirculation rate of 6%. Dairy S's average hydraulic loading rate was 0.7 cm d^{-1}, and nearly 50% of effluent from the 2nd Vr was dosed into the influent of the 2nd Vr, with recirculation of 12 times per day, lasting 1 h each time.

2.4. Sampling and analysis

Water samples were collected at the inlet and the final outlet of each bed, either monthly or bimonthly. At the sampling time, bottles were thoroughly rinsed with water to be sampled, and environmental parameters such as pH, electrical conductivity (EC), DO, oxidation–reduction potential (ORP), and water temperature (T) were recorded *in situ* during field measurement. After sampling, water quality indicators such as biochemical oxygen demand (BOD_5), suspended solid (SS), and total coliform (T. Coli.) were analyzed immediately. Water samples for COD, ammonium-N (NH_4-N), TN, Nitrate-N (NO_3-N), Nitrite-N (NO_2-N), Organic-N (Org-N), Total phosphorus (TP) were stored in a refrigerator for laboratory analysis. Analysis methods referred to Standard Methods for the Examination of Water and Wastewater (APHA, 1992),[26] and Testing Methods for Industrial Wastewater (JIS, 1998).[27]

2.5. Water flow

Water flow rate was calculated by measuring the changes in the siphon tank's water table positions. The water table was recorded every 10 min using a pressure-type water-level gauge equipped with a data logger (DL/N70; Sensor Technik. Sirnach (STS) AG, Sirnach, Switzerland, or S&DLmini Oyo Corp., Tokyo, Japan). Flow rate was adjusted to account for the amount of precipitation and the estimated amount of evapotranspiration in each bed.

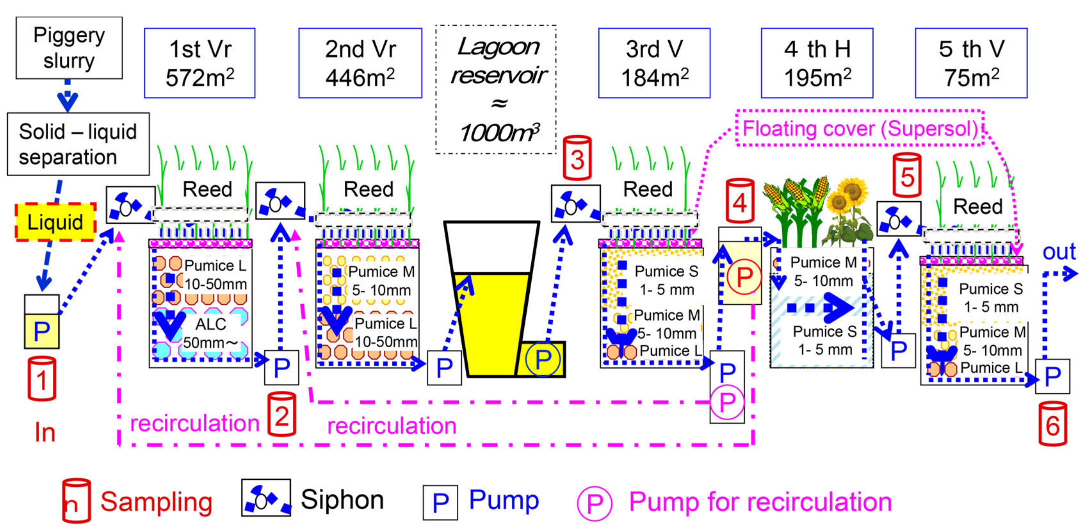

Figure 2. Schematic diagram of the hybrid subsurface flow CW system (piggery O).

Table 2. Area, stages, wastewater type, bed material, and number of livestock of three hybrid subsurface flow CW systems.

Hybrid system	Area (m^2)	Stages	Wastewater	Bed material	Numbers of livestock
Piggery O	1472	Vr-Vr-V-H-V	Swine urine wastewater	Pumice gravel	2000
Dairy G	3048	Vr-V-V-H-V	Milking parlor wastewater	Sand	500
Dairy S	656	V-Vr-H	Milking parlor wastewater	Sand, river gravel, clinker ash	120

Note: V, VF bed; Vr, VF bed with recirculation; H, HF bed.

2.6. Treatment calculation

Purification efficiency (PE), RE, and removal rate were calculated as follows:

$$\text{PE (\%)} = (C_{in} - C_{out}) \times 100/C_{in}$$

$$\text{RE (\%)} = (L_{in} - L_{out}) \times 100/L_{in}$$

$$\text{Removal rate } (g\,m^{-2}d^{-1}) = L_{in} - L_{out},$$

$$L(g\,m^{-2}d^{-1}) = (\text{Concentration} \times \text{Flow rate})/\text{Bed area},$$

where C_{in} and C_{out} are the pollutant concentrations in influent and effluent, respectively. L is the pollutant load in wastewater, while L_{in} and L_{out} are the pollutant loads in influent and effluent, respectively, with a unit of g m^{-2} d^{-1}.

3. Results and discussion

3.1. Environmental parameters

Table 3 shows average pH, T, DO, EC, and ORP at the inlet and outlet of each bed, at the final outlet of each system, as well as average water flow rates. Compared with air temperature, water temperature in these systems varied from 10.0 ± 8.0°C to 16.3 ± 8.0°C. The ORPs at each inlet and final outlet were normally positive, with an average value of around 100–300 mV, which created anaerobic conditions. Piggery O's pH values ranged from 7.0 to 8.3, while those of dairy G and dairy S ranged from 6.0 to 7.0. The DO varied between 2.2 and 4.8 mg L^{-1} in piggery O, 2.4 and 3.2 mg L^{-1} in four of dairy G's beds (dairy G's 1st Vr bed was 5.1 mg DO L^{-1}), and 1.8 and 2.1 mg L^{-1} in dairy S. The EC was higher in piggery O compared with dairy G and dairy S. Dairy G had a higher flow rate of around 30.2–38.7 m^3 d^{-1} compared with 4.7–5.9 m^3 d^{-1} for dairy S.

3.2. Pollutant PE

Piggery O, dairy G, and dairy S were monitored and evaluated during their respective five, three, and eight years of operation. Table 4 shows pollutant concentrations at the inlet of each bed and final outlet, along with overall PE in each system.

Piggery O's average influent TN concentration was as high as 1395 mg L^{-1} compared with dairy G's 267 mg L^{-1} and dairy S's 155 mg L^{-1}. TN concentration in all systems decreased gradually after wastewater passed through each bed. The final effluent TN concentrations for dairy G and dairy S were 34 ± 13 and 21 ± 15 mg L^{-1}, respectively; those levels were below the 60 mg L^{-1} threshold set by Japanese water quality regulators. Dairy G and dairy S had TN purification efficiencies of 86 ± 8% and 85 ± 12%, respectively, while for piggery O PE was around 70 ± 9%. Piggery O's efficiency was around the same order of magnitude reported by Vymazal and Kröpfelová,[28] and was higher than most systems mentioned in a review by Vymazal.[29]

Table 3. Environmental parameters and flow rate at the inlet of each bed and final outlet of three hybrid subsurface flow CW systems.

			1st bed	2nd bed	3rd bed	4th bed	5th bed	Out
Piggery O	pH		8.3 ± 0.5	8.0 ± 0.5	7.7 ± 0.5	7.7 ± 0.6	7.5 ± 0.6	7.0 ± 0.7
	T	°C	16.3 ± 8.0	12.7 ± 7.5	11.6 ± 7.3	11.0 ± 7.7	10.9 ± 7.8	10.6 ± 8.1
	DO	mg L^{-1}	2.2 ± 2.7	3.3 ± 2.9	3.8 ± 2.0	4.4 ± 2.5	3.9 ± 2.8	4.8 ± 2.8
	ORP	mV	117 ± 140	203 ± 90	231 ± 87	249 ± 96	278 ± 82	322 ± 84
	EC	mS cm^{-1}	10.5 ± 2.8	6.2 ± 1.5	5.1 ± 0.7	4.7 ± 0.6	4.3 ± 0.6	3.8 ± 0.6
	Flow rate	m^3 d^{-1}	10.4 ± 6.4	27.7 ± 18.5	42.7 ± 27.3	12.2 ± 6.9	12.4 ± 7.1	12.5 ± 7.2
Dairy G	pH		6.3 ± 1.0	6.0 ± 0.3	6.5 ± 0.2	6.7 ± 0.2	6.8 ± 0.2	6.8 ± 0.3
	T	°C	13.3 ± 4.5	12.0 ± 5.9	11.6 ± 6.1	11.3 ± 6.5	10.2 ± 6.3	10.7 ± 5.8
	DO	mg L^{-1}	5.1 ± 2.3	2.7 ± 1.5	3.2 ± 1.8	2.4 ± 1.5	3.0 ± 1.6	2.5 ± 1.5
	ORP	mV	239 ± 38	213 ± 58	192 ± 68	184 ± 71	203 ± 74	285 ± 50
	EC	mS cm^{-1}	0.8 ± 0.2	0.8 ± 0.2	0.8 ± 0.2	0.8 ± 0.2	0.8 ± 0.2	0.7 ± 0.2
	Flow rate	m^3 d^{-1}	30.2 ± 3.7	33.4 ± 4.0	35.1 ± 5.5	37.5 ± 7.9	38.3 ± 8.5	38.7 ± 8.9
Dairy S	pH		6.6 ± 0.6	6.8 ± 0.4	6.9 ± 0.3			6.9 ± 0.5
	T	°C	12.8 ± 6.6	12.7 ± 7.4	11.0 ± 6.5			10.0 ± 8.0
	DO	mg L^{-1}	1.8 ± 1.6	1.8 ± 1.2	2.1 ± 1.1			1.9 ± 1.2
	ORP	mV	203 ± 63	223 ± 64	216 ± 69			258 ± 83
	EC	mS cm^{-1}	1.2 ± 0.3	1.2 ± 0.2	1.1 ± 0.2			0.8 ± 0.2
	Flow rate	m^3 d^{-1}	4.7 ± 0.8	4.9 ± 1.0	5.0 ± 1.3			5.9 ± 2.2

Note: T, temperature; DO, dissolved oxygen; ORP, oxidation-reduction potential; EC, electrical conductivity.

Table 4. Pollutants' concentrations at the inlet of each bed and final outlet, and the purification efficiency (PE).

			1st bed	2nd bed	3rd bed	4th bed	5th bed	Outlet	PE (%)
Piggery O	TN	mg L^{-1}	1395 ± 321	670 ± 205	508 ± 147	471 ± 133	396 ± 104	397 ± 103	70 ± 9
	NH_4-N	mg L^{-1}	1130 ± 460	484 ± 244	326 ± 141	274 ± 132	221 ± 118	135 ± 102	85 ± 14
	TP	mg L^{-1}	151 ± 62	36 ± 25	28 ± 12	24 ± 9	19 ± 8	13 ± 4	90 ± 6
	COD	mg L^{-1}	6512 ± 3471	1764 ± 1198	1049 ± 599	865 ± 453	627 ± 262	442 ± 192	91 ± 6
	BOD_5	mg L^{-1}	1962 ± 1740	442 ± 442	174 ± 127	135 ± 91	85 ± 51	50 ± 33	95 ± 4
	SS	mg L^{-1}	3073 ± 1352	1088 ± 580	736 ± 331	604 ± 293	472 ± 213	293 ± 172	94 ± 14
	T. Coli.	CFU $100mL^{-1}$	2701 ± 4417	167 ± 287	51 ± 49	47 ± 116	22 ± 24	13 ± 29	94 ± 18
Dairy G	TN	mg L^{-1}	267 ± 71	92 ± 31	73 ± 23	54 ± 15	46 ± 17	34 ± 13	86 ± 8
	NH_4-N	mg L^{-1}	24 ± 42	33 ± 15	32 ± 18	27 ± 15	26 ± 13	14 ± 10	40 ± 240
	TP	mg L^{-1}	54 ± 15	24 ± 7	21 ± 6	18 ± 6	15 ± 6	13 ± 5	76 ± 9
	COD	mg L^{-1}	9846 ± 2652	2457 ± 873	1620 ± 579	944 ± 299	542 ± 235	382 ± 164	96 ± 2
	BOD_5	mg L^{-1}	5609 ± 2261	1190 ± 449	730 ± 266	338 ± 135	153 ± 125	106 ± 81	98 ± 2
	SS	mg L^{-1}	2534 ± 885	362 ± 177	173 ± 53	96 ± 41	33 ± 21	23 ± 10	84 ± 11
	T. Coli.	CFU $100mL^{-1}$	567 ± 491	2626 ± 4368	1623 ± 2700	1943 ± 4748	583 ± 804	387 ± 408	70 ± 38
Dairy S	TN	mg L^{-1}	155 ± 59	81 ± 35	46 ± 29			21 ± 15	85 ± 12
	NH_4-N	mg L^{-1}	67 ± 27	46 ± 28	28 ± 27			13 ± 11	76 ± 28
	TP	mg L^{-1}	25 ± 11	19 ± 7	14 ± 6			6 ± 3	71 ± 29
	COD	mg L^{-1}	3751 ± 2118	1153 ± 853	549 ± 482			212 ± 196	94 ± 5
	BOD_5	mg L^{-1}	1450 ± 585	708 ± 364	288 ± 162			92 ± 79	94 ± 4
	SS	mg L^{-1}	650 ± 491	127 ± 144	45 ± 58			13 ± 16	97 ± 4
	T. Coli.	CFU $100mL^{-1}$	12,337 ± 23,356	6165 ± 10,579	1401 ± 1613			113 ± 239	97 ± 10

Notes: TN, Total N; NH_4-N, ammonium-N; TP, Total phosphorus; COD, chemical oxygen demand; BOD_5, biochemical oxygen demand; SS, suspended solid; T. Coli., total coliform. CFU 100 mL^{-1} means colony-forming units per 100 milliliters sampled water.

Treatment of NH_4-N was similar in piggery O and dairy S; the concentration decreased gradually at each bed and the PE was 85 ± 14% and 76 ± 28%, respectively. In dairy G on the other hand, NH_4-N concentration initially increased after the 1st V, and then decreased gradually in the subsequent four beds. Dairy G's NH_4-N removal pattern may be attributed to the high content of Org-N in its influent. When incoming wastewater has high Org-N, ammonification initiates the first step of N transformation (nitrification) in the subsurface flow wetland systems.[3] Figure 3 shows nitrogen composition. Org-N and NH_4-N accounted for 91% and 9% of dairy G's TN, respectively. Figure 3 also shows increasing NO_3-N content at each of piggery O's beds, likely due to the oxidation of NH_4-N to NO_3-N by nitrification.

Piggery O, dairy G, and dairy S had total P purification efficiencies in the amount of 90 ± 6%, 76 ± 9%, 71 ± 29% with an incoming concentration of 151 ± 62, 54 ± 15, and 25 ± 11 mg L^{-1}, respectively. Piggery O's influent wastewater had a high TP content but its system had higher PE. This could be attributed to the use of pumice gravel as the bed material. Pumice gravel can potentially enhance treatment efficiency of P due to its high P adsorption capacity.[20]

Piggery O, dairy G, and dairy S had COD influent concentrations in the amount of 6512 ± 3471, 9846 ± 2652, and 3751 ± 2118 mg L^{-1}, respectively. All systems had high purification efficiencies in excess of 90%, which was higher than the system treating swine wastewater with an influent COD of 4421 ± 454 [30] and 1115–1160 mg L^{-1}.[31] The BOD_5 PE was above 90% in each system. Both COD and BOD_5 concentrations decreased greatly in the 1st V bed, which is consistent with other studies.[7,20,29]

Piggery O, dairy G, and dairy S had high SS and T. Coli. purification efficiencies. In dairy G, however, T. Coli. concentrations increased sharply after passing through the

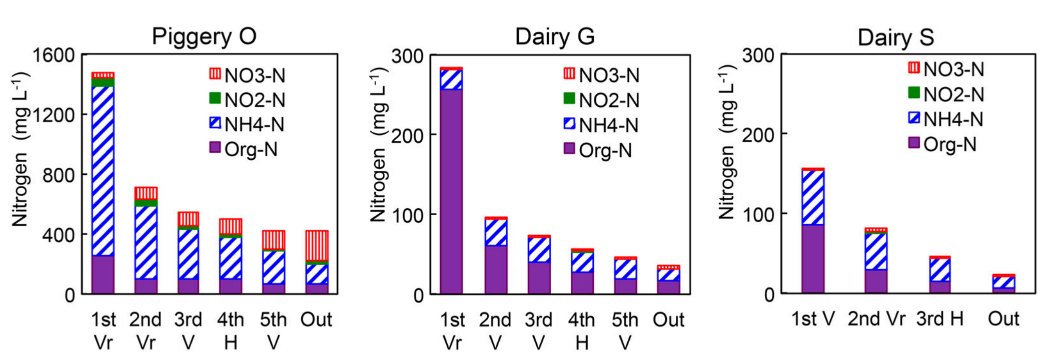

Figure 3. Nitrogen composition at the inlet of each bed and final outlet of three hybrid subsurface flow CW systems. NO_3-N, nitrite-N; NO_2-N, nitrate-N; NH_4-N, ammonium-N; Org-N, organic-N.

1st Vr. This may be due to the high organic content, which could encourage T. Coli. growth.

3.3. Pollutant load, removal, and yearly variations

Figure 4 shows average original influent load and final effluent load, as well as RE for each hybrid system.

TN removal rates in piggery O, dairy G, and dairy S were 6.1 ± 4.1, 2.2 ± 0.9, and 0.9 ± 0.4 g TN m^{-2} d^{-1}, respectively. Compared with the removal rates reported by Vymazal,[29] piggery O's removal rate was higher than the highest TN average removal rate (4.2 ± 5.1 g TN m^{-2} d^{-1}), but dairy G's removal rate was similar. Dairy S had the lowest removal rate. This may be associated with the increased N load, which typically coincides with greater removal rate in subsurface flow wetland systems.[3] Kato et al. [20,21] reported that high influent load would lead to high removal rate. In piggery O, dairy G, and dairy S, the influent TN loads were 9.4 ± 5.0, 2.7 ± 0.9, and 1.1 ± 0.5 g TN m^{-2} d^{-1}, respectively. Overall TN removal efficiencies were 62 ± 19%, 82 ± 9%, and 82 ± 15% and NH_4-N removal efficiencies were 6.4 ± 4.6, 0.1 ± 0.5, and 0.4 ± 0.2 g TN m^{-2} d^{-1} in piggery O, dairy G and dairy S, respectively.

Piggery O, dairy G, and dairy S showed TP removal rates in the amount of 0.9 ± 0.8, 0.4 ± 0.2, and 0.1 ± 0.1 g TP m^{-2} d^{-1}, respectively. The latter findings are similar to findings reported by Vymazal.[29] Total removal efficiencies were 86 ± 10%, 70 ± 11%, and 65 ± 25% for piggery O, dairy G, and dairy S, respectively.

COD removal rates were 46.4 ± 49.2, 94.1 ± 36.6, and 25.1 ± 15.5 g COD m^{-2} d^{-1} for piggery O, dairy G, and dairy S, respectively. Dairy G had a higher influent load of 98.9 ± 37.1 g COD m^{-2} d^{-1} compared with 26.9 ± 16.0 g COD m^{-2} d^{-1} for dairy S. Total COD removal efficiencies for piggery O, dairy G, and dairy S were 88 ± 10%, 95 ± 3%, and 92 ± 7%, respectively. Dairy G also had highest removal rate of BOD_5, in the amount of 57.7 ± 28.4 g m^{-2} d^{-1}.

Figure 5 shows annual influent and final effluent load levels of TN, NH_4-N, TP, COD, and BOD_5, in the form of box-and-whisker diagrams, along with annual RE for each system. Piggery O's load of TN, NH_4-N, TP, COD, and BOD_5 was highest in its first year, compared with the following four years. Piggery O's removal efficiencies increased year after year, particularly in the case of TN, where the RE increased from 38% in the 1st year to 62% in the 2nd year. This could be explained by an increase of microorganisms involved in N transformation and the gradual improvement of conditions for N removal. Dairy G's influent load of TP stayed at a consistent level during these three years, but TP RE decreased. This could be due to saturation of the sand's adsorption capacity over time. Dairy G's overall removal efficiencies for COD and BOD_5 were around 95% since operation commenced. For dairy S, removal efficiencies of COD and BOD_5 were stable and high at around 90%. Dairy S had some small fluctuations in TN and TP removal rates during the recent years, but the system still performed well.

3.4. Correlations between environmental parameters and pollutant RE

Pearson correlation coefficients were estimated using SPSS 19.0 to evaluate correlations between environmental parameters and RE.

Table 5 shows correlations between pollutant RE of TN, NH_4-N, TP, COD, and BOD_5 and environmental parameters such as COD/TN ratio, DO, and *T*.

Overall, temperature had no significant effect on COD and BOD_5 RE at each bed of every system. This could be expected on the basis of findings reported by Steinmann et al. [32] and Akratos et al.,[33] which indicated that organic matter removal was not significantly affected by temperature. For piggery O, temperature had a significant positive effect on NH_4-N removal at the 4th H bed. For dairy S, on the other hand, temperature had a

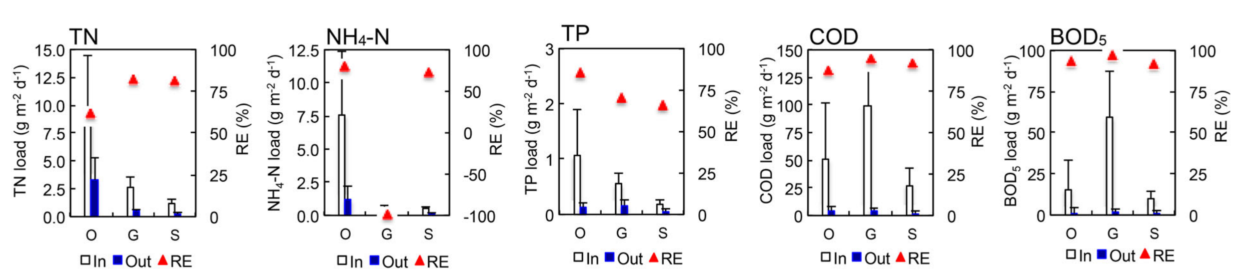

Figure 4. Pollutant load at the original influent (In) and final effluent (Out), and the total removal efficiency (RE) of each hybrid system. Bars represent standard deviations. TN, Total N; NH_4-N, ammonium-N; TP, Total phosphorus; COD, chemical oxygen demand; BOD_5, biochemical oxygen demand.

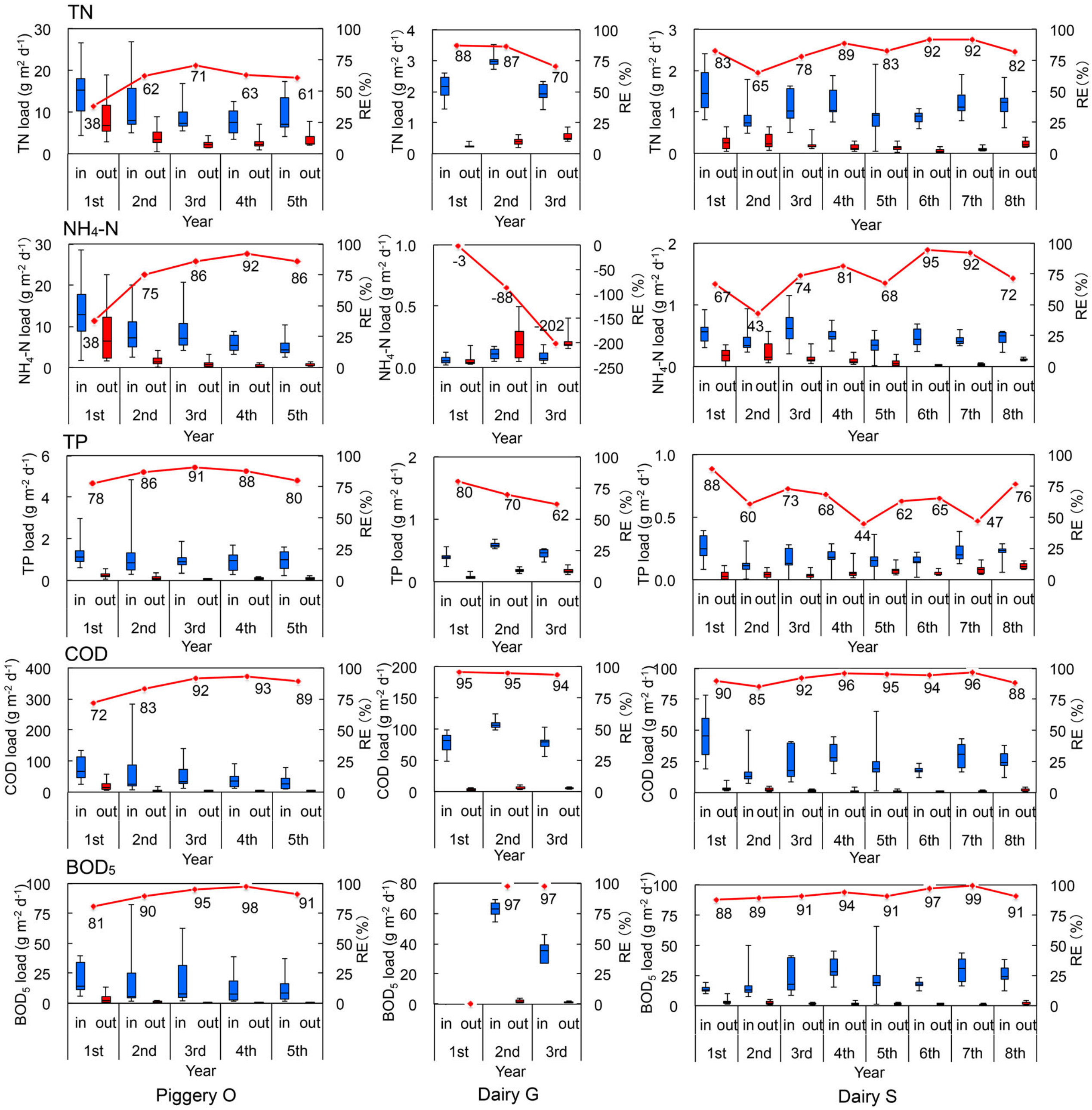

Figure 5. Yearly pollutants' influent load (inlet) and effluent load (outlet), and the yearly removal efficiency (RE) of each hybrid subsurface flow CW system. TN, Total N; NH_4-N, ammonium-N; TP, Total phosphorus; COD, chemical oxygen demand; BOD_5, biochemical oxygen demand.

significant positive effect on NH_4-N removal at the 1st Vr and 2nd V beds.

The amount of DO might have had a significant positive effect on NH_4-N removal in piggery O, but a negative correlation was observed in dairy S. Some studies indicated that effluent DO from a wetland is not necessarily a good indicator of the wetland matrix's aerobic/anaerobic conditions.[34]

The COD/TN ratio varied significantly, with average levels around 2–5, 12–37, and 12–23 for each bed in piggery O, dairy G and S, respectively. Although COD/TN ratio varied in these systems, a similar relationship was observed, that is, there was a significant negative correlation between COD/TN ratio and NH_4-N RE. This could be attributed to the fact that a high COD load would likely consume oxygen for degradation, thereby affecting nitrification to some extent.[18] Further, organic compounds are needed to serve as electron donors for denitrification. When organic compounds are insufficient, denitrifcation may be limited.

Table 5. Correlations (Pearson coefficient) between environmental parameters and pollutant removal efficiency removal efficiency (RE).

		Piggery O			Dairy G			Dairy S		
		T	DO	COD/TN	*T*	DO	COD/TN	*T*	DO	COD/TN
1st bed	TN	0.10	0.11	−0.13	−0.34	0.11	−0.66*	0.32	−0.06	0.09
	NH_4-N	−0.09	0.18	−0.31*	−0.19	−0.05	−0.14	0.56*	−0.23*	−0.36**
	TP	0.12	0.10	−0.07	−0.25	−0.03	−0.42*	−0.10	0.08	0.14
	COD	0.01	0.17	0.02	−0.23	−0.02	−0.48*	0.03	−0.14	0.04
	BOD_5	0.00	0.19	0.02	0.27	−0.48	−0.57*	0.26	0.02	−0.07
2nd bed	TN	−0.03	0.07	0.02	0.36	−0.61**	−0.31	0.18	−0.07	−0.34**
	NH_4-N	0.06	0.18	−0.31*	0.30	−0.25	−0.45*	0.63**	0.19	−0.28*
	TP	−0.19	0.10	0.34*	0.19	−0.06	0.14	0.29	−0.29**	−0.05
	COD	0.19	0.00	0.41**	0.30	−0.38	0.17	−0.08	−0.01	0.32**
	BOD_5	0.07	0.10	0.24	0.18	−0.14	0.06	−0.12	0.11	0.23*
3rd bed	TN	−0.07	0.07	0.01	0.37	−0.26	−0.14	−0.02	0.08	0.16
	NH_4-N	−0.25	0.43**	−0.41**	0.33	−0.05	−0.18	−0.39	0.21	0.07
	TP	−0.28*	0.03	0.22	0.15	0.07	0.33	0.18	0.34**	0.11
	COD	0.17	−0.16	0.15	0.39	−0.25	−0.17	−0.38	0.15	0.20
	BOD_5	0.22	−0.35**	0.37**	0.31	−0.30	−0.18	−0.43	−0.02	−0.10
4th bed	TN	0.19	−0.19	0.16	−0.16	0.34	0.74**			
	NH_4-N	0.41**	−0.33*	0.02	0.22	0.03	0.29			
	TP	0.22	−0.50**	0.51**	−0.28	0.34	0.27			
	COD	0.23	−0.39**	0.45**	0.28	−0.26	0.30			
	BOD_5	0.09	−0.12	0.05	0.49	−0.51	−0.12			
5rd bed	TN	−0.14	0.05	0.40**	0.17	0.01	0.16			
	NH_4-N	0.21	−0.13	−0.39**	−0.21	0.04	0.08			
	TP	0.11	−0.17	0.24	0.36	0.07	−0.06			
	COD	0.19	−0.31*	0.30*	0.06	−0.05	0.34			
	BOD_5	0.29	−0.40**	0.18	−0.19	−0.60*	0.27			

Notes: *T*, temperature (°c); DO, dissolved oxygen (mg L^{-1}).
*Significant at the $p < 0.05$ level.
**Significant at the $p < 0.01$ level.

4. Conclusions

The three hybrid subsurface flow CW systems observed in this study were able to effectively treat high content wastewater in cold climate conditions. TN, NH_4-N, TP, COD, BOD_5, SS, and T. Coli. PEs were 70–86%, 40–85%, 71–90%, 91–96%, 94–98%, 84–97%, and 70–97%, respectively. Piggery O, which used pumice gravel bed material, had the highest TP PE. Observation of the systems showed a correlation between high TP loads and high removal rates. Piggery O had the highest TN removal rate, 6.1 ± 4.1 g TN m^{-2} d^{-1}, with an influent load of 9.4 ± 5.0 g TN m^{-2} d^{-1}. Dairy G had the highest COD removal rate, 94.1 ± 36.6 g COD m^{-2} d^{-1}, with an influent load as high as 98.9 ± 37.1 g COD m^{-2} d^{-1}. All three systems had a total COD RE of around 90%. Over each system's whole operational period, the data showed stable and efficient performance during cold climate conditions. The COD/TN ratio might adversely affect nitrification in these systems. Overall, the results of this study show that hybrid subsurface flow CW systems can effectively and efficiently treat piggery and milking parlor wastewater.

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Disclosure statement

No potential conflict of interest was reported by the authors.

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