Design and performance of hybrid reed bed systems for treating high content wastewater in the cold climate

Kunihiko Kato
NARO Tohoku Agricultural Research Center, Morioka, Iwate, Japan

Takashi Inoue
Hokkaido University

Hidehiro Ietsugu

Pradeep Kumar Sharma
Graphic Era University

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K. Kato[1], T. Inoue[2], H. Ietsugu[3], T. Koba[4], H. Sasaki[5], N. Miyaji[6], T. Yokota[1, 7], P. K. Sharma[2], K. Kitagawa[3] and T. Nagasawa[2]

[1] National Agricultural Research Center for Hokkaido Region, Hitsujigaoka-1, Toyohira-ku, Sapporo 062-8555, Japan (E-mail: *katokuni@affrc.go.jp*)
[2] Graduate School of Agriculture, Hokkaido University
[3] TUSK Co., Ltd.
[4] Hokkaido Prefectural Konsen Agricultural Experiment Station
[5] Kankyo-Engineering Co., Ltd
[6] College of Humanities and Sciences, Nihon University
[7] Reed NET Co., Ltd

Abstract
We designed, constructed and evaluated the performance of six real scale hybrid reed bed systems for treating four kinds of high content wastewater in the cold climate in Hokkaido, Northern Japan. First is for dairy wastewater (three systems, average inflow 4.8 – 24.5 $m^3.d^{-1}$, 2,400 - 5,000 $mg.COD.l^{-1}$, 2 – 4.6 years operation). Second is for potato starch processing wastewater (one system, 7 - 20 $m^3.d^{-1}$, 24,000 - 54,000 $mg.COD.l^{-1}$, 2 years operation). Third is for pig farm liquid food washing wastewater (one system, 4.9 $m^3.d^{-1}$, 9,500 $mg.COD.l^{-1}$, 1.6 year operation), and the last is for swine urine wastewater (one system, 15.1 $m^3.d^{-1}$, 10,100 $mg.COD.l^{-1}$, 7 months operation). Our systems are composed of three to four VF beds and none or one HF bed (total of three to five beds). The total bed areas are 168 to 2,151 m^2. Mean annual temperature is around 5 to 8 centigrade at all systems. To overcome clogging during freezing cold climates, we applied following countermeasures; i.e., safety bypass structure at each bed, floating cover material for the VF bed surface, partition and rotational use of VF bed surface for growing season, and use of self-priming siphon for every VF bed. Water was circulated in some beds to improve performance mainly in growing season. Average purification rates were 70 - 96% for COD, 39 - 90% for TN, 36 - 82 % for NH_4-N, 70 - 93 % for TP. Average load were 33 - 234 $g.COD.m^{-2}.d^{-1}$, 1.3 – 17.8 $g.TN.m^{-2}.d^{-1}$ and 0.21 - 1.10 $g.TP.m^{-2}.d^{-1}$. Calculated average oxygen transfer rates (OTR) were 17 - 139 $g.O_2.m^{-2}.d^{-1}$. As a result, our systems proved to be able to treat high content wastewater, operating in high load and OTR, overcoming the problem of clogging in the cold climates.

Keywords
cold climate; dairy milking parlor; hybrid reed bed system; potato starch processing; swine urine

INTRODUCTION

Dairy milking parlor wastewater, potato starch processing wastewater and swine urine wastewater's treatment has been a big problem in Hokkaido, northern Japan because these wastewaters are polluting rivers and groundwater. Conventional mechanical wastewater treatments are expensive. So, there is an urgent need to apply a low cost technology for the treatment of such kind of wastewaters. Constructed wetlands for pollution control have been greatly progressed over the past 20 years (P. Cooper 2009; J. Vymazal 2009; R. H. Kadlec et al. 2000). However there are still some limitations for the treatment of high content wastewater in cold climates. So we designed and constructed a new hybrid reed bed system to treat high content wastewaters in the cold climates between 2005 and 2009. We describe design and performance of all these systems.

SYSTEM DESIGN AND METHODS

We designed, constructed and evaluated the performance of six real scale hybrid reed bed plants for treating high content wastewater in the cold climate in Hokkaido, Northern Japan. The outline of our plants is shown in **Table 1** and **Table 2**. There are four kinds of high content wastewater. First is for dairy milking parlor wastewater treatment (three systems, 120 – 380 milking cows, 2 – 4.6 years operation). Second is for potato starch processing wastewater treatment (one system, high content decanter wastewater, 2 years operation). Third is for pig farm liquid food washing wastewater treatment (one system, 1.6 years operation), and the last is for swine urine wastewater (one system, 2000 pigs, 7 months operation).

Each plant is composed of 3 to 5 reed beds, combined with vertical flow (with or without circulating pump) and horizontal flow reed beds.

Table 1. Stages, types of beds and wastewater.

Name of Plant	Stage of beds	Type of beds *	Type of wastewater	Cattles number
K dairy farm (K)	4	V + V + H + V	Dairy milking parlour	380 milking cows
S dairy farm (S)	3	V + Vc + H	Dairy milking parlour	120 milking cows
N dairy farm (N)	4	V + Vc + H + V	Dairy milking parlour	300 milking cows
P starch processing (P)	5	Vc + Vc + Vc + H + Vc	Potato starch processing	
A pig food (A)	3	Vc + Vc + V	Pigery liquid feeding	
O pig urine (O)	5	V + V + V + H + V	Swine urine	2000 pigs

* V: vertical flow; H: horizontal flow; Vc: vertical flow with circulating pump

Mean temperature, rainfall, assessment period and assessment number are shown in **Table 2**. All reed bed plants worked throughout the year except P starch processing factory's plant which worked from May to Nov. Mean annual temperature is around 5 to 8 centigrade at almost all systems. All plants were constructed between 2005 to 2009.

Table 2. Place, temperature, rainfall, assessment period and assessment number.

Plant	Town	Mean air temperature in Centigrade*	Mean railfall in mm	Assesment Period (years) *	Assesment number
K	Bekkai	5.3	1139	Nov. 2005 - Jun. 2010 (4.6y)	98
S	Embetsu	6.4	1053	Nov. 2006 - Jun. 2010 (3.6y)	54
N	Bekkai	5.3	1139	Jun. 2008 - Jun. 2010 (2.0y)	22
P1	Kiyosato	15.1 (May-Aug.)	271 (May-Aug.)	May-Aug. in 2009, May-Jun. in 2010	7
P2		9.0 (Sep.-Nov.)	252 (Sep.-Nov.)	Sep. - Nov. in 2008 and 2009	10
A	Atsuta	7.6	1111	Nov. 2008 - Jun. 2010 (1.6y)	17
O	Chitose	7.1	977	Nov. 2009 - Jun. 2010 (0.6y)	14

* All plants work throughout the year except P, starch factory, which works from May to Nov.

Mean inflow, bed area, bed type and main bed material are shown in **Table 3**. Volcanic pumiceous gravel or sand, river gravel or sand, shale gravels and coal-fired electric power station’s clinker ash were used as the bed materials. Mean inflow of wastewater was from 7 to 24 m^3/d.

Our reed bed systems basically follow French and Danish systems in operation for the treatment of domestic wastewater (Molle et al. 2005; Brix et al. 2005). The size of each reed bed was designed with reference to the estimated ability of nitrification, COD and NH_4-N removal and denitrification (Cooper 2005; Obarska-Pempkowiak et al. 2003) and to prevent from clogging (Winter et al. 2003).

Table 3. Mean inflow, bed area, bed type and main bed material.

Plant	Mean inflow (m^3/d)	Bed area (m^2)					
		1st	**2nd**	**3rd**	**4th**	**5th**	**Total**
		Bed type* / Main bed material**					
K dairy	24.5	256	256	512	150	-	1174
		V / PG	V / RS	H / PG	V / PG		
S dairy	4.8	160	160	336	-	-	656
		V / RG	Vc / CA	H / RS			
N dairy	15.5	645	484	484	176	-	1789
		V / PG	Vc / PG	H / PG	V / PG		
P1	21 (May-Aug.)	990	510	294	210	147	2151
P2	7 (Sep.-Nov.)	Vc / PG	Vc / PG	Vc / PS	H / PG	Vc / PS	
A pig food	4.9	96	48	24	-	-	168
		Vc / SG	Vc / SG	V / SG			
O pig urine	15.1	572	446	184	195	75	1472
		V / PG	V / PG	V / PG	H / PG	V / PG	

* V : vertical flow bed; H: horizontal flow bed; Vc: vertical flow bed with circulating pump
**: PG = Pumiceous Gravel, PS = Pumiceous Sand, RG = River Gravel, RS = River Sand, SG = Shale Gravel, CA = Clinker Ash

To treat high content wastewater and to overcome clogging in the cold climates, we applied following countermeasures (Kato et al. 2009); i.e., safety bypass structure at each bed, floating cover material for the VF bed surface, partition and rotational use of VF bed surface for growing season, and use of self-priming siphon for every VF bed (**Figure 1** and **Figure 2**). Water has been circulating in some beds to improve performance mainly in growing season.

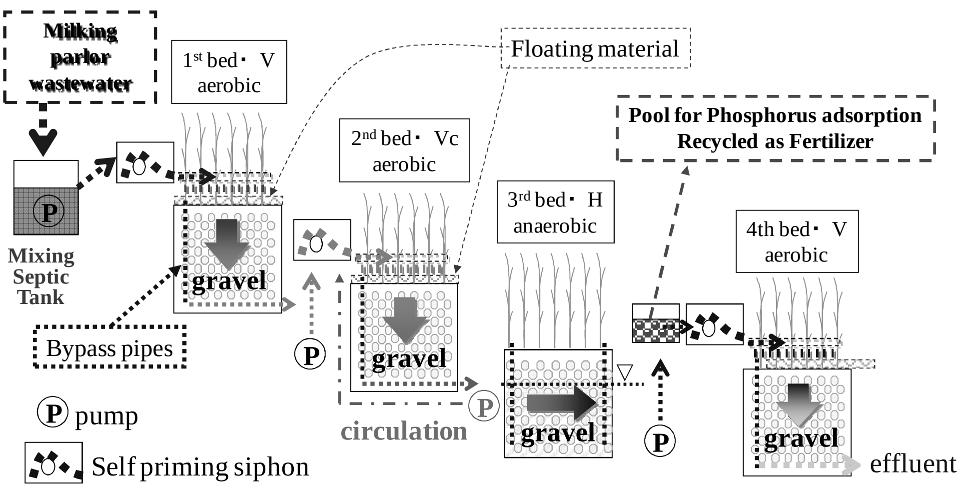

Figure 1. Schematic diagram of a hybrid reed bed system (N dairy farm).

Sacrificial P-sorption material was experimentally used for purification of phosphorus in K dairy, N dairy and P starch factory, and the absorbed phosphorus would be recycled to farmland (**Figure 1**).

We prepared organic matter application pool in front of HF bed to accelerate denitrification based on the result from preliminary experiment in the laboratory studies (Kato et al. 2005, 2006). But we didn't have chance to apply organic matter because of excessive organic matter in the treated water in real scale.

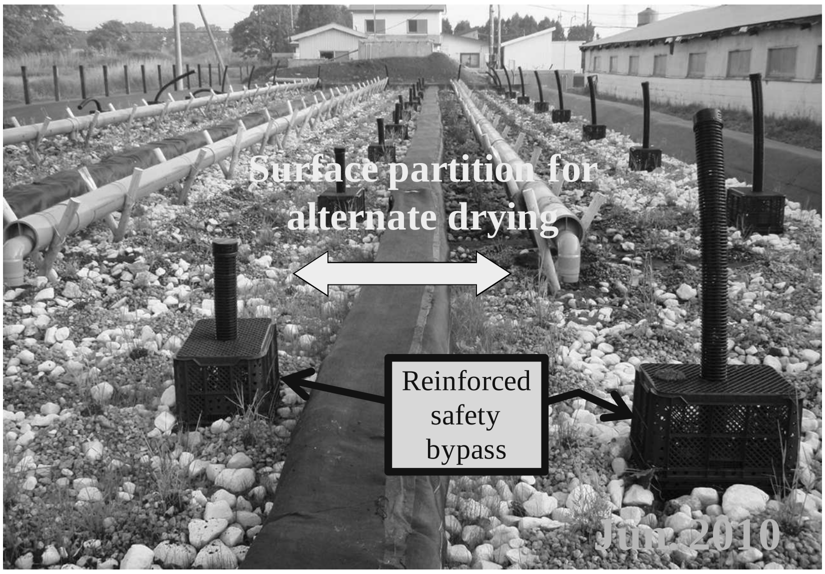

Figure 2. Surface partition and reinforced safety bypass (O pig farm).

We measured the amount of water flow and collected water samples at inlet and outlet of each reed bed. The amount of water flow was measured by counting movement of each self-priming siphon.

Chemical oxygen demand (COD), total nitrogen (T-N), ammonium nitrogen (NH_4-N), total phosphorus (T-P) in the samples were analyzed in the laboratory.

PERFORMANCE

All plants worked throughout the assessment period and did not stop for a single time even during winter period and did not freeze in winter.

Mean pollutant concentration of inter-stage data and purified rate are shown in **Table 4**.

Influent wastewater concentration is 2,400 – 54,000 mgCOD.l^{-1}, 100 – 4,100 mgT-N.l^{-1}, 7 – 1,800 mgNH_4-N.l^{-1} and 19 – 338 mgT-P.l^{-1}. Average purification rates were 70 - 96% for COD, 39 - 90% for T-N, 36 - 82 % for NH_4-N, 70 - 93 % for T-P. Average load, removed load and oxygen transfer rate (OTR) of total system are shown in **Table 5**. Average load were 33 - 234 g.COD.m^{-2}.d^{-1}, 1.3 – 17.8 g.TN.m^{-2}.d^{-1} and 0.21 - 1.10 g.TP.m^{-2}.d^{-1}. Average removal load were 29 - 221 g.COD.m^{-2}.d^{-1}, 1.0 – 12.0 g.TN.m^{-2}.d^{-1} and 0.16 - 1.02 g.TP.m^{-2}.d^{-1}. Average OTRs are 17 - 139 g.O_2.m^{-2}.d^{-1}in total system.

Purification rate, load, removal load were calculated using the following equations (1) – (3). The dimension of concentration (Conc.) is in mg.l^{-1} and that of flow rate is in m^3.d^{-1}.

Purification rate % = 100 ((Conc. in – Conc. out) / Conc. in) (1)
*Load = (flow rate * Conc. in) / bed area* (2)
*Removed load = ((flow rate in * Conc. in) – (flow rate out * Conc. out)) / bed area* (3)

OTR was calculated using the following equation (4) (Cooper 2005). The ratio of COD:BOD was about 0.5 in our plants' wastewater. The dimension of COD and NH_4-N concentrations are in mg.l^{-1}

$$OTR = flow\ rate\ (0.5\ (COD\ in - COD\ out) + 4.3\ (NH_4\text{-}N\ in - NH_4\text{-}N\ out))\ /\ bed\ area \quad (4)$$

Table 4 Mean pollutant concentration of inter-stage data and purification rate.

Plant	(mg L^{-1})	Influent	1st	2nd	3rd	4th	5th	Purified %
K dairy	COD	2385	1081	528	235	142	-	94
	T-N	101	72	47	31	37	-	63
	NH_4-N	35	42	29	24	13	-	62
	T-P	21.7	16.7	10.6	7.0	6.6	-	70
S dairy	COD	4107	1368	659	269	-	-	93
	T-N	167	93	55	28	-	-	83
	NH_4-N	76	59	39	19	-	-	75
	T-P	25.9	17.9	11.7	4.4	-	-	83
N dairy	COD	5002	1819	630	342	211	-	96
	T-N	198	86	43	26	22	-	89
	NH_4-N	38	40	22	15	7	-	82
	T-P	37.6	22.2	13.2	6.8	4.5	-	88
P1 preserved *	COD	24017	14502	6985	2933	2923	2000	92
	T-N	1425	887	520	345	308	260	82
	NH_4-N	1030	812	881	525	366	267	74
	T-P	99	62	32	27	25	20	80
P2 fresh *	COD	54065	29095	11138	5184	4364	3214	94
	T-N	4118	2187	1054	615	555	424	90
	NH_4-N	1311	1225	839	505	502	369	72
	T-P	338	118	58	37	30	25	93
A pig food	COD	9555	3839	1640	579	-	-	94
	T-N	202	103	48	23	-	-	89
	NH_4-N	7	33	17	9	-	-	
	T-P	18.5	12.8	3.9	1.4	-	-	92
O pig urine	COD	10112	9585	7100	6333	4603	3059	70
	T-N	1866	1787	1492	1383	1257	1134	39
	NH_4-N	1798	1532	1408	1307	1184	1157	36
	T-P	115	108	81	60	39	26	77

* P1 was preserved wastewater from May to August and P2 was fresh wastewater from September to November.

Table 5. Average load, removal and OTR of total system.

Plant	COD(Cr) g.m^{-2}.d^{-1}		T-N g.m^{-2}.d^{-1}		T-P g.m^{-2}.d^{-1}		OTR
	Load	Removal	Load	Removal	Load	Removal	gO_2.m^{-2}.d^{-1}
K dairy	42	38	1.8	1.0	0.38	0.22	22
S dairy	33	29	1.3	1.0	0.21	0.16	17
N dairy	43	41	1.7	1.5	0.35	0.31	22
P1 preserved	234	215	13.9	11.4	0.96	0.77	139
P2 fresh	176	165	13.4	12.0	1.10	1.02	96
A pig food	233	221	5.3	4.7	0.39	0.35	113
O pig urine	97	67	17.8	6.7	1.10	0.84	65

Oxygen transfer rate (OTR) and type of reed bed
We evaluated the performance of every bed, by calculating OTR. To compare reed beds' performance in different locations, the effects of temperature on OTR performance could be adjusted from T (= mean air temperature of each site) to T' (= 5.3 centigrade) by using the equation (5) referring the modified Arrhenius equation (Kadlec R. H. et al. 2000). Here, the temperature coefficient θ was assumed at 1.05. The values in **Table 2** were used for mean air temperature T in each location.

$$OTR' / OTR = \theta^{(T'-20)} / \theta^{(T-20)} \quad (5)$$

Figure 3 shows relationship between load (COD and NH_4-N load) and adjusted OTR' (T' = 5.3 centigrade).

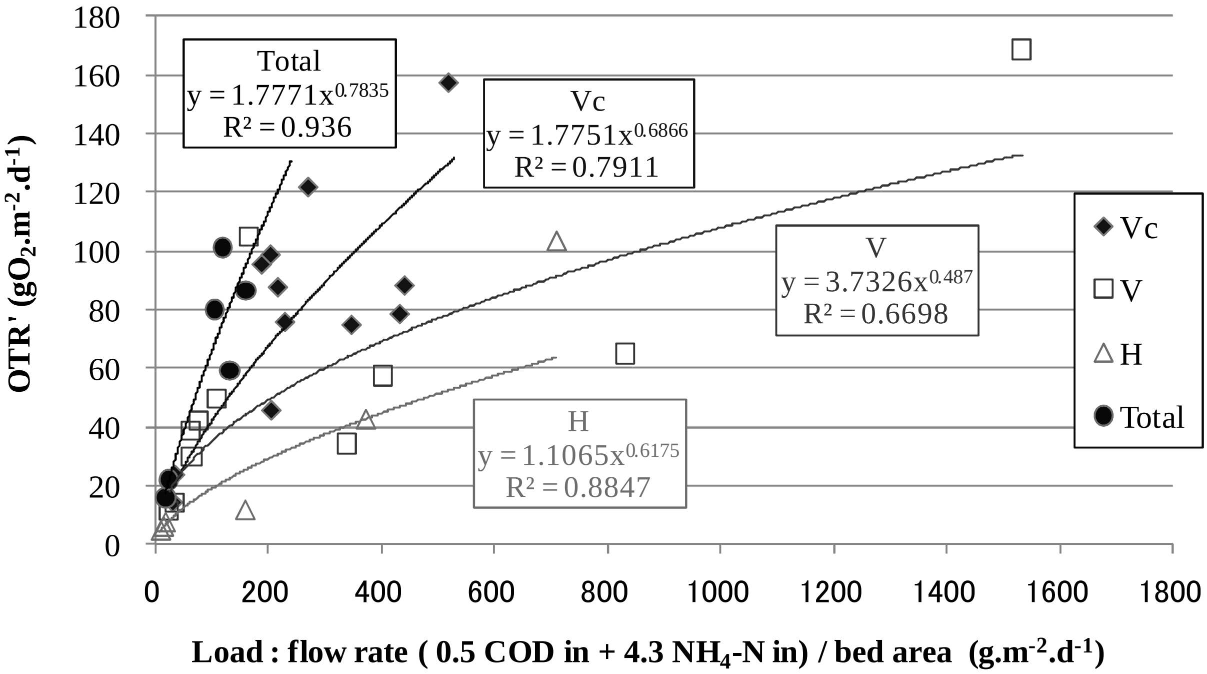

Figure 3. COD and NH_4-N load and OTR' adjusted with mean air temperature of each location.

The OTR' increased in proportion to influent load. The OTR' increasing rate is highest in vertical flow beds with circulating pump (Vc), medium in vertical flow bed (V) and lowest in horizontal flow beds (H). It seems to be not impossible to design more effective reed bed system by using the performance data as those in **Figure 3**, with collecting more precise data in advance.

CONCLUSION
As a result, our systems proved to be able to treat high content wastewater, operating in high load and OTR, overcoming the problem of clogging in the cold climates.

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REFERENCES

Brix H. and Arias C.A. (2005). The use of vertical flow constructed wetlands for on-site treatment of domestic wastewater: new Danish guidelines. *Ecological Engineering* 25, 491-500.

Cooper P. (2009). What can we learn from old wetlands? Lessons that have been learned and some that may have been forgotten over the past 20 years. *Desalination* 24, 11–26

Cooper P. (2005). The performance of vertical flow constructed wetland systems with special reference to the significance of oxygen transfer and hydraulic loading rates. *Wat. Sci. Tech.* 51(9), 81–90.

Kadlec R. H., Knight R. L., Vymazal J., Brix H., Cooper P. and Harbel R. (2000). Constructed wetlands for pollution control, processes, performance, design and operation. By IWA Specialist Group on Use of Macrophytes in Water Pollution Control, Scientific and Technical Report No.8, IWA publishing.

Kato K., Sharma P., Inoue T., Ietsugu H., Koba T., Kitagawa K., Tomita K., Matsumoto T. and Nagasawa T. (2009). New design of hybrid reed bed constructed wetland system for the treatment of milking parlor wastewater in cold climate conditions of Hokkaido, northern Japan. *IWA Specialist Group on Use of Macrophytes in Water Pollution Control: Newsletter* 34, 8-12.

Kato K., T. Koba T., Ietsugu H., Saigusa T., Yanagiya S, Inoue T., Kitagawa K. and Kobayashi S. (2007). First Year Performance of a Real-Scale Hybrid Wetland System for the Treatment of Dairy Wastewater in a Cold Climate in Japan. *2nd International Symposium on Wetland Pollutant Dynamics and Control.* Extended abstracts, VOLUME I, Tartu, Estonia, 150-152.

Kato K., Koba T., Ietsugu H., Saigusa T., Nozoe T., Kobayashi S., Kitagawa K. and Yanagiya S. (2006). Early Perpormance of hybrid reed bed system to treat milking parlour wastewater in cold climate in Japan. *10th International Conference on Wetland Systems for Water Pollution Control.* Lisbon, Portugal, 1111-1118.

Kato K., Morioka R., Hosokawa H., Osada T., Kanazawa K. and Nozoe T. (2005). Preliminary studies on hybrid wetland systems for purification of milking parlor wastewater in northern part of Japan. *Abstracts of International Symposium on Wetland Pollutant Dynamics and Control,* Gent, Belgium, 250-251

Molle P., Liénard A., Boutin C., Merlin G., Iwema A. (2005). How to treat raw sewage with constructed wetlands: An overview of the French systems. *Wat. Sci. Tech.* 51(9), 11–21.

Obarska-Pempkowiak H., Gajewska M. (2003). The removal of nitrogen compounds in constructed wetlands in Poland, *Polish Journal of Environmental Studies.* 12(6), 739-746.

Winter K. J., Goetz D. (2003). The impact of sewage composition on the soil clogging phenomena of vertical flow constructed wetlands. *Wat. Sci. Tech.,* 48 (5), 9-14.

Vymazal J. (2009) The use constructed wetlands with horizontal sub-surface flow for various types of wastewater. *Ecological Engineering* 35, 1–17