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Performance of six multi-stage hybrid wetland systems for treating high-content wastewater in the cold climate of Hokkaido, Japan

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ABSTRACT

The performance of six multi-stage hybrid wetland systems, which were designed and constructed for treating high-content wastewater, was evaluated in the cold climate of Hokkaido, northern Japan. The systems were designed to treat four kinds of wastewater: dairy wastewater (three systems, average inflow 4.9–46.6 $m^3\,d^{-1}$, average inflow content 2400–5000 mg COD l^{-1}, 2–5 years of operation); wastewater from a pig farm, including liquid food washing wastewater (one system, 4.1 $m^3\,d^{-1}$, 9500 mg COD l^{-1}, 2 years of operation); wastewater from potato starch processing (one system, 5.4–13.3 $m^3\,d^{-1}$, 24,000–54,000 mg COD l^{-1}, 2 years of operation); and wastewater containing pig farm swine urine (one system, 16.9 $m^3\,d^{-1}$, 10,100 mg COD l^{-1}, 1 year operation). Our systems were composed of three to four vertical (V) flow beds with self-priming siphons and surface partitions and no or one horizontal (H) flow bed (total of three to five beds). In some V flow beds, treated effluents were recirculated (Vr) through the inlet to improve performance, mainly during the growing season. The total bed area was 168–2151 m^2. Mean annual temperature was 5–8 °C at all locations. To overcome clogging due to the high load in a cold climate, we applied a safety bypass structure and floating cover material (Supersol: lightweight porous glass) to the V flow beds. The safety bypass structure and floating cover material helped to prevent clogging and freezing and maintained dry conditions and abundant growth of reeds and earthworms. The average purification rates were 70–96% for chemical oxygen demand (COD), 39–90% for total nitrogen (TN), 36–82% for NH_4–N, and 70–93% for total phosphorous (TP). Calculated average oxygen transfer rates (OTRs) were 16–99 g $O_2\,m^{-2}\,d^{-1}$. OTRs increased in proportion to influent load, and the OTR value was Vr > V > H. Recirculating the treated effluents was expected to enhance removal of nitrogen in V flow beds mainly by a combination of nitrification and denitrification. By treating higher organic loads per area without clogging, it was possible to minimize the area and cost of treating high-content wastewater. However, more data are needed concerning load and OTR to design a more efficient multi-stage wetland system.

1. Introduction

Japan's food self-sufficiency ratio is only about 40%, which is remarkably low compared to other industrialized countries. A large surplus of nitrogen and phosphorus is given to animals as feed, which is mostly imported from abroad (Yano et al., 1999). Moreover, the nitrogen and phosphorus from animal manure exceed fertilizer needs because of the small area of farmland in Japan. Treatment of dairy milking parlor wastewater, potato starch processing wastewater, and swine urine wastewater has been a

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Table 1
Location, temperature, rainfall, assessment period and number of sampling times.

System	Town name	Mean air temperature in Centigrade[a]	Mean rainfall mm/year[a]	Assessment period (years)[b]	Number of sampling times (n)
Dairy K	Bekkai	5.3	1142	November 2005–November 2010 (5.0 years)	104
Dairy S	Embetsu	6.8	1023	November 2006–November 2010 (4.0 years)	61
Dairy N	Bekkai	5.6	1221	June 2008–June 2010 (2.0 years)	22
Pig food A	Atsuta	8.3	1371	November 2008–November 2010 (2.0 years)	21
Starch P1[c]	Kiyosato	15.1 (May–August)	271 (May–August)	June–August 2009, May–August 2010	7
Starch P2[c]		9.0 (September–November)	252 (September–November)	September–November 2009 and 2010	10
Pig urine O	Chitose	7.6	1113	November 2009–November 2010 (1.0 years)	31

[a] From Automated Meteorological Data Acquisition System (AMeDAS) of Japan Meteorological Agency.
[b] All systems work throughout year except starch factory P which works from May to November.
[c] P1 was preserved wastewater from May to August and P2 was fresh wastewater from September to November.

big problem in Hokkaido, northern Japan, where such wastewaters are polluting rivers and groundwater. Conventional mechanical wastewater treatments are expensive. Thus, there is an urgent need for a low-cost technology for treating such wastewater. Constructed wetlands for pollution control have progressed greatly over the past 20 years (Cooper, 2009; Vymazal, 2009; Kadlec et al., 2000). Moreover, hybrid systems have been in use since the 1980s (Vymazal and Kröpfelová, 2011). Several important studies about the selection of filter media, the treatment performance at low temperature, and the recirculation effect have been conducted in cold climates (Poldvere et al., 2009, 2010; Jenssen et al., 2005, 2010; Speer et al., 2012). However, issues of clogging and freezing for treating high-content wastewater in cold climates still remain. To overcome these issues, we designed and constructed multi-stage hybrid reed bed systems in 2005 with a safety bypass and a floating cover to treat high-content wastewater in the cold climate of Hokkaido, Japan (Kato et al., 2006, 2009). Our hybrid systems are basically a combined hybrid system (Obarska-Pempkowiak and Gajewska, 2003; Poldvere et al., 2009; Vymazal and Kröpfelová, 2011), including a French-type reed bed system (Molle et al., 2005) and a Danish system with recirculation in a vertical (V) flow reed bed (Brix and Arias, 2005). Here, we describe the design and performance of the six hybrid systems.

2. System design and methods

2.1. System design, climate, and other information

Six multi-stage hybrid wetland systems were designed for treating high-content wastewater in the cold climate of Hokkaido, northern Japan (Kato et al., 2010; Sharma et al., 2011).

Mean temperature, rainfall, assessment period, and assessment number are shown in Table 1. The system of dairy farm K is located at N 43°26′ latitude and E 144° 52′ longitude, dairy S system is located at N 44°45′ lat. and E 141°48′ long., dairy N system is located at N 43°28′ lat. and E 145°04′ long. Pig food A system is located at N 43°21′ lat. and E 141°26′ long., starch P system is located at N 43°49′ lat. and E 144°33′ long., and pig urine O system is located at N 42°49′ lat. and E 141°44′ long.

Annual average air temperature was 5–8 °C at all locations. The lowest monthly average daily temperatures in Bekkai, Embetsu, Atsuta, and Chitose were −14.2, −11.9, −8.4, and −12.7 °C, and the highest monthly average temperatures were 18.1, 20.0, 20.7, and 20.8 °C, respectively. All reed bed plants were active throughout the year, except at the potato starch processing plant, which was designed to work only during the growing season.

Four kinds of high-content wastewater needed to be treated. The first was dairy milking parlor wastewater (three systems, 120–380 milking cows, average inflow 4.9–46.6 $m^3 d^{-1}$, average inflow content 2400–5,000 mg·chemical oxygen demand (COD) l^{-1}, 2–5 years of operation). The second was pig farm liquid food washing wastewater (one system, 4.1 $m^3 d^{-1}$, 9500 mg COD l^{-1}, 2 years of operation). The third was potato starch processing wastewater (one system, high-content decanter wastewater, 5.4–13.3 $m^3 d^{-1}$, 24,000–54,000 mg COD l^{-1}, 2 years operation), and the last was swine urine wastewater (one system, 2000 pigs, 16.9 $m^3 d^{-1}$, 10,100 mg COD l^{-1}, 1 year operation).

2.2. Schematic diagram

A schematic diagram of the hybrid wetland system is shown in Fig. 1. Our systems are composed of three to four V flow beds with a self-priming siphon and no or one horizontal (H) flow bed with a total of three to five beds. A French-type self-priming siphon was applied for the V flow bed with minor modifications; each dosing pipe was single for simplicity and easy maintenance (Kato et al., 2006, 2009). Some effluents were recirculated (Vr) to the inlet in some V beds with a pump to improve performance, mainly during the growing season. The water will freeze if too much effluent is recirculated in winter. Vr referred to recirculation within a single bed in this study.

2.3. Clogging and freezing countermeasures

The main issues of dense wastewater treatment in cold climates are clogging and freezing. We applied a safety bypass structure at each bed and covered the V-flow bed surface with a floating cover material (Supersol; TRIM Co., Ltd., Okinawa, Japan) to treat the dense wastewater and to overcome clogging in a cold climate (Fig. 2).

2.3.1. Bypass mechanism to avoid clogging

Bulky organic matter in the influent nutrient load leads to clogging in the bed, which results in failure of the whole system. A bypass or "emergency door" system was designed in the bed to avoid clogging. The bypass was composed of perforated pipes connecting the bed surface to the bed bottom. When the bed surface was temporarily clogged and percolation stopped, wastewater moved downward through these perforated pipes and drained water. Although the nutrient removal efficiency of the bed decreased during the temporary clogging phase using this mechanism, it provided a margin to remove excess load and avoid fatal clogging and helped vegetation and earthworms. The perforated pipes were often reinforced with a surrounding container cover, and perforated pipes inside the container were made with larger holes than those in the container to achieve sustainable percolation performance (Fig. 2).

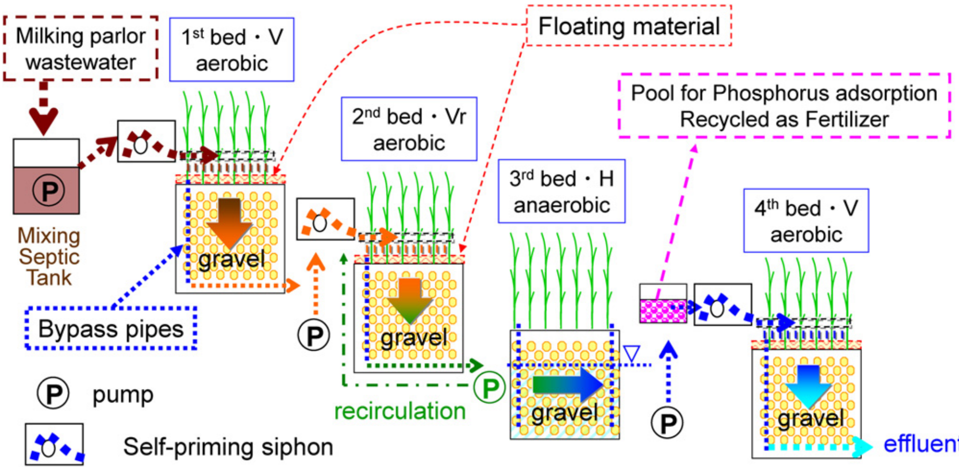

Fig. 1. A schematic diagram of the hybrid wetland system (example; dairy N).

2.3.2. Use of floating material (Supersol) on top of the beds

Supersol is a lightweight porous material that is manufactured from waste glass bottles (TRIM Co., Ltd., 2012). Its density is 0.4 g cm^{-3}, and it floats on the water. Pores inside the Supersol are not connected to the outside, so Supersol floats. Supersol has the advantage of preventing clogging and freezing in cold climates. Partial surface flow will subsequently occur at the time of influent dosing when the bed surface is partially clogged. Supersol floats on the flooded surface and acts as an obstruction to surface flow in the influent pipes between the perforated bypass pipes, trapping bulky organic matter. Thus, Supersol changes the partial flooded surface flow to subsurface flow. In this way, Supersol helps prevent clogging of the bed surface and drying of the bed.

During winter months, Supersol act as an insulating material and helps prevent freezing conditions on the top of the bed (Kato et al., 2009).

2.4. Bed area, material, surface partition, and vegetation

The bed area, surface cover material, main bed material, number of surface partitions, and vegetation are described in Table 2.

The area of each reed bed for treatment of the wastewater from the dairy farm milking parlor was designed with reference to the estimated COD and NH_4–N removal (Cooper, 2005; Molle et al., 2005). The systems were designed to treat a higher organic load per area for denser non-dairy wastewater treatment.

Fig. 2. Surface partition and reinforced safety bypass (pig urine O).

Volcanic pumiceous gravel or sand, river gravel or sand, shale gravel, and coal-fired electric power station clinker ash were used as the main bed materials. Volcanic pumice, shale, and clinker ash are porous, whereas river gravel and sand are non-porous.

Some of the bed surfaces were covered with three kinds of materials to act as a heat-resistant layer in the cold climate, including larch wood chips, lightweight porous glass (Supersol), and autoclaved aerated lightweight concrete (ALC) (Table 2). The depth of these surface cover materials was 4–5 cm. The Supersol and ALC floated on the water due to their low specific gravity. The specific gravity of Supersol is 0.4 g cm^{-3} and that of ALC is 0.5–0.6 g cm^{-3}.

The surface of the early stage V flow bed was partitioned into two or three zones with reference to French systems and used alternately to maintain dry conditions during the growing season (Molle et al., 2005). The resting and feeding periods were 1–2 weeks. The benefit of surface drying during the growing season was to accelerate percolation by adding cracks in the organic clogging cover on the surface. Sufficient evapotranspiration to dry the surface was expected during the growing season. The number of partitions in each bed is shown in Table 2.

Common reeds (*Phragmites australis*) grown from seeds or reed stems were planted as seedlings in pots. Cattails were planted as seeds directly in several beds mixed with common reeds. Wild weeds were allowed to grow freely in almost every bed. In some H flow beds, we planted rice, upland crops, wetland flowers, and fruits such as blueberry and haskap (*Lonicera caerulea var. emphyllocalyx*) experimentally. Haskap is a Japanese wild fruit that grows in Hokkaido.

2.5. Flow measurement

Water flow was calculated by monitoring the change in the water table at each self-priming siphon or pumping hall. The change in the water table was measured every 5–10 min with a pressure-type water-level gauge and a data logger (DL/N70; Sensor Technik. Sirnach (STS) AG, Sirnach, Switzerland or S&DL Mini; Oyo Corp., Tokyo, Japan) throughout the year.

2.6. Sampling and quality measurement

Water samples were collected at every inlet and outlet of each reed bed. Samples were taken once per month and analyzed immediately for COD, NH_4–N, total nitrogen (T-N), and total phosphorus

Table 2
Bed type and area, surface cover and main bed material, surface partition and vegetation.

System	1st	2nd	3rd	4th	5th	Total bed area
	Bed type[a]/bed area (m^2) Suface cover material[b]/main bed material[c]/no. of surface partitions[d] Main vegetation[e]					
Dairy K 1[f]	V/256 SS/PG/no Ph, C, O	V/256 no/RS/no Ph	H/512 WC/PG/no Ph	V/150 ALC/PG/no Ph, O	–	1174
Dairy K 2[f]	V/512 SS/PG/2 Ph, C, O	V/512 SS/RS/2 Ph, O	H/512 WC/PG/no Ph	V/150 ALC/PG/no Ph, O	–	1686
Dairy S	V/160 SS/RG/2 Ph	Vr/160 SS/CA/2 Ph	H/336 ALC/RS/no RE, Ph, C, O	–	–	656
Dairy N	V/645 SS, ALC/PG/2 Ph, C, O	Vr/484 ALC/PG/2 Ph, O	H/484 ALC/PG/no WE, O, FE	V/176 ALC/PG/no WE, O	–	1789
Pig food A	Vr/96 SS/SG/3 Ph	Vr/48 ALC/SG/2 Ph	V/24 ALC/SG/no Ph	–	–	168
Starch P	Vr/990 ALC/PG/3 Ph, O	Vr/510 ALC/PG/2 Ph, O	Vr/294 ALC/PS/2 Ph, O	H/210 no/PG/no UE, O	Vr/147 ALC/PS/2 Ph, O	2151
Pig urine O	V/572 ALC/PG/3 Ph, O	V/446 SS, ALC/PG/2 Ph, O	V/184 SS, ALC/PG/2 Ph	H/195 no/PG/no UE, FE	V/75 SS, ALC/PG/no Ph, O	1472

[a] V, vertical flow; H, horizontal flow; Vr, vertical flow with recirculation pump; Vr, vertical flow with recirculation pump and recirculation within a single bed.
[b] SS = Supersol (recycled porous glass); ALC = autoclaved lightweight aerated concrete; WC = wood chip.
[c] PG = Pumicious Gravel; PS = Pumicious Sand; RG = River Gravel; RS = River Sand; SG = Shale Gravel; CA = Clinker Ash.
[d] The partitioned bed was used altenetely for drying in the growing season.
[e] Ph = Phragmites (common reed); C = cattails; O = other weed; RE = rice for experiment; UE = upland crops for experiment; WE = wetland flower for experiment; FE = fruit tree for experiment.
[f] K plant was upgraded for increase of wastewater since March 2010.

(T-P). COD was measured with a spectrophotometer (Hach DR2800, Loveland, CO, USA) using a digital reactor (Hach DRB200) and disposable COD digestion vials (Hach). NH_4–N was measured with a segmented-flow analysis system (QuAAtro; SEAL Analytical Gmbh, Norderstedt, Germany). T-N was measured with an elemental analyzer (Elementar vario MAX; Elementar Analysensysteme GmbH, Hanau, Germany). T-P was measured with a colorimeter using the molybdenum blue ascorbic acid reduction method after decomposition by peroxodisulfate (JIS K0102 46.3.1, Japan).

3. Results and discussion

3.1. System running conditions

The minimum air temperatures were −28.0, −24.5, −15.2, and −23.1 °C at Bekkai, Embetsu, Atsuta, and Chitose, respectively, all between December and March. All systems worked throughout the assessment period and did not freeze during the winter.

An example of the temperature change through the system at dairy farm K is shown in Fig. 3. Effluent water (3rd H or 4th V) temperature was always positive, even when the daily average air temperature was −15 °C. The minimum effluent water temperature was 1–3 °C, and was lowest during the snow-melting season.

Surface partition or floating cover material was not used in the V flow bed of the first system at dairy farm K in its first year of operation, and consequently, the system became clogged in spring and autumn. Beginning with the second growing season of 2006, the surface was partitioned for rotational drying, and beginning with the third growing season in 2007, the surface was covered with the Supersol floating material. The safety bypass in the V flow bed was reinforced at dairy farm K in 2008. The clogging material then disappeared gradually. Since 2008, both a reinforced safety bypass and floating cover material have been adopted, and no severe clogging has been seen.

Because Supersol is relatively expensive, ALC was adopted as an alternative floating material in the third system (dairy farm N) in 2008. ALC also floats on water initially, but it did not continue to float and was less stable than Supersol. Therefore, Supersol is used mainly as the floating cover material for new reed bed systems. The stable floating ability of Supersol is attributable to its independent cavities, which are not connected to the outside. It is similar to a small stable floater aggregate made from waste glass bottles (TRIM Co., Ltd., 2012).

3.2. Average flow rate of each system

The average flow rate of each bed of six systems during the assessment period is shown in Table 3. Water flow was calculated by monitoring the self-priming siphon water table of each VF bed. The flow rate without a siphon was estimated using meteorological data. Larger outflow than inflow was attributed to more precipitation than evapotranspiration.

Table 3
Average flow rate of each system bed ($m^{-3}\ d^{-1}$).

System	Inflow	1st[a]	2nd[a]	3rd[a]	4th[a]	5th[a]
K 1	22.5	24.8	25.3	26.0	33.1	
K 2	46.6	49.9	52.0	51.3	51.9	
S	4.9	5.2	5.6	6.9		
N	15.3	17.6	19.4	21.1	21.8	
A	4.1	4.5	4.7	4.8		
P 1	13.3	15.3	16.6	17.5	17.6	17.8
P 2	5.4	6.6	7.3	7.8	8.2	8.4
O	16.9	17.8	18.5	18.7	19.0	19.1

[a] Value for the first to the fifth bed is the out flow of each bed.

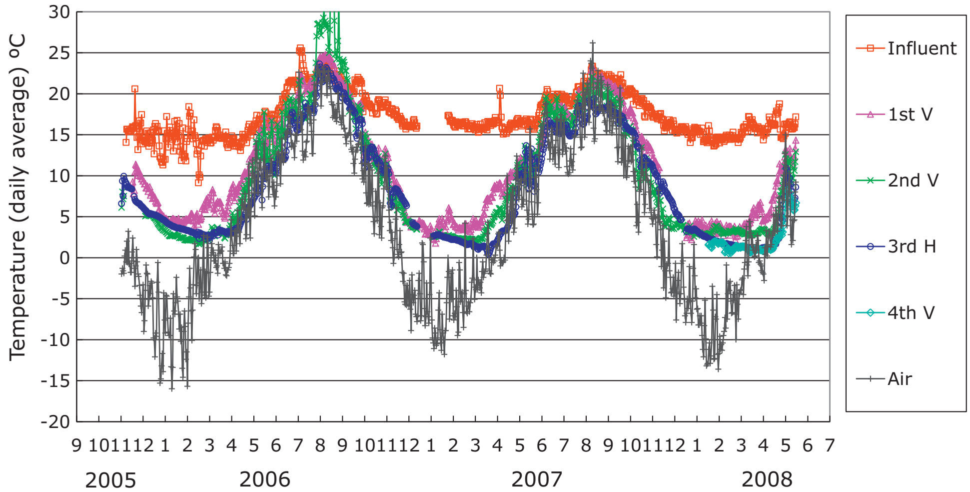

Fig. 3. Air and water temperature changes at the dairy farm K system in Bekkai.

3.3. Concentration decrease in the inter-stage data

Average pollutant concentrations in the inter-stage data from the potato starch factory (P), pig farm food (A), pig farm swine urine (O), and dairy farms (K, S, and N) are shown in Fig. 4. The left-side axes (non-dairy) in the figure have a 10 times larger scale than the right-side axes (dairy). Every pollutant (COD, T-P, NH_4–N, and T-N) decreased through the reed bed stages in the non-dairy and dairy farms. Even the starch factory wastewater influent with a content of >50,000 mg COD l^{-1} decreased to <5000 mg COD l^{-1}, which is almost the same content as the dairy wastewater influent. Thus, it was possible to decrease wastewater content by adding reed bed stages.

The average purification rates were 70–96% for chemical oxygen demand (COD), 39–90% for total nitrogen (TN), 36–82% for NH_4–N, and 70–93% for total phosphorous (TP).

3.4. Oxygen transfer rate (OTR) and type of reed bed

The performance of every bed was evaluated by calculating OTRs (Cooper, 2005). The influent COD load plus NH_4–N was defined as

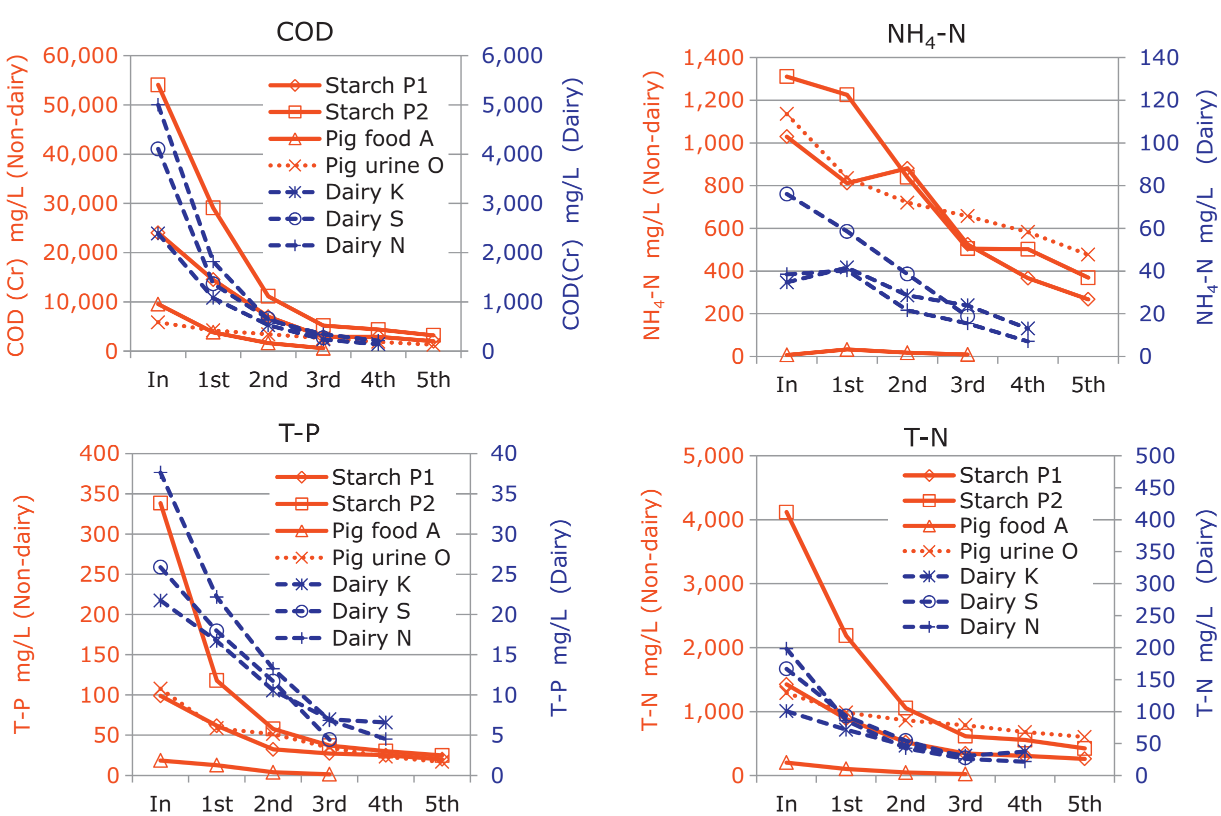

Fig. 4. Average pollutant concentrations in the inter-stage data.
*P1, preserved potato starch wastewater from May–August; P2, fresh wastewater from September to November.

Table 4
Load of oxygen necessity (LON) and oxygen transfer rate (OTR) values of inter-stage data.

System	LON (gO_2 m^{-2} d^{-1})						OTR (gO_2 m^{-2} d^{-1})					
	1st	2nd	3rd	4th	5th	Total	1st	2nd	3rd	4th	5th	Total
K 1	117	69	19	38		26	55	31	8	17		23
K 2	108	34	20	33		33	77	15	10	21		32
S	72	29	8			18	45	13	4			16
N	63	39	16	29		23	37	25	7	12		22
A	188	195	174			108	99	111	109			99
P 1	120	190	244	198	249	55	35	60	110	25	74	46
P 2	223	286	302	222	284	102	102	130	153	32	82	93
O	264	300	620	541	1212	102	42	53	55	82	157	55

the load of oxygen necessity (LON). The OTR and LON were calculated using Eqs. (1) and (2). In our experiment, the average influent and effluent BOD/COD ratio was approximately 0.5, and thus, the ratio of BOD/COD was set to 0.5 in the calculation. This is quite similar to the BOD/COD ratio in fresh domestic sewage in the UK (Cooper, 2005). The units for COD, NH_4–N, flow rate, and bed area are mg l^{-1}, mg l^{-1}, m^3 d^{-1}, and m^2, respectively.

$$\mathrm{OTR} = \frac{\text{flow rate}\{0.5(\text{COD in} - \text{COD out}) + 4.3(\text{NH}_4\text{-Nin} - \text{NH}_4\text{-Nout})\}}{\text{bed area}} \quad (1)$$

$$\text{Load of oxygen necessity(LON)} = \frac{\text{flow rate}(0.5\text{CODin} + 4.3\text{NH}_4\text{-Nin})}{\text{bed area}} \quad (2)$$

Average loads and OTRs in the inter-stage data are shown in Table 4. Total OTR values in the dairy farm systems were 16–32, but OTR values in the non-dairy systems were 46–99. The LON and OTR values decreased from the first to the third bed in systems K, S, and N, but were almost the same through the first to third beds in systems A, P, and O. This was related to the bed area ratio of the first: second: third beds in systems K, S, and N, which was about 1:1:2; the bed area of systems A, P, and O decreased from the first to the third bed at a ratio of 4:2:1 through the first to third beds (Table 2).

3.5. Temperature effect

Several biogeochemical processes that regulate nutrient removal in wetlands are affected by temperature, which thus influences overall treatment efficiency. The temperature effects of surface flow treatment wetlands are often described through a modified Arrhenius temperature-dependent Eq. (3) as follows (Kadlec and Reddy, 2001; Kadlec et al., 2000):

$$k = k_{20}\theta^{(T-20)} \quad (3)$$

where k = areal removal rate constant, k_{20} = areal removal rate constant at 20 °C, T = temperature (°C), θ = temperature coefficient.

To compare the performance of the hybrid reed beds in different locations, the OTR where temperature = T was adjusted to OTR′, where temperature = T', using Eq. (4) referring to the modified Arrhenius Eq. (3). A temperature coefficient θ = 1.05 was assumed in the calculation, based on organic matter and ammonium nitrogen temperature coefficients reported in previous studies (Kadlec and Reddy, 2001; Siracusa and La Rosa, 2006). The average air temperature in Table 1 was applied for each location.

$$\frac{\mathrm{OTR}'}{\mathrm{OTR}} = \frac{\theta^{(T'-20)}}{\theta^{(T-20)}} \quad (4)$$

Fig. 5 shows the relationship between load and adjusted OTR′ (T' = 5.3 °C). The 5.3 °C temperature was the annual average temperature of the town of Bekkai, where the first dairy K system was constructed. The OTR′ increased in proportion to influent load. The rate of OTR′ increase was highest in the V flow beds with the recirculating pump (Vr), medium in the V flow beds, and lowest in the H flow beds.

OTR′ values for high influent loads were >40 and some were >80, which were higher than the recommended OTR value of 28 (Cooper, 2005). OTR′ values for low influent loads were almost the same or less than the recommended OTR value of 28.

It is possible to design multistage reed bed systems with Vr, V, and H, by using the performance data shown in Fig. 5. By treating a higher organic load per area without clogging, it will be possible to minimize the area required and cost of treating high-content wastewater. However, the relationship of load to OTR is expected to change depending on the properties of the wastewater, the climate, and the maturity of the wetland system. Thus, more data are needed concerning loads and OTRs to design a more accurate multi-stage wetland system.

3.6. Effect of recirculation

The average received load and removed load for each reed bed are shown in Fig. 6. V flow, vertical flow with recirculation (Vr), and H flow are shown with different symbols. The received load and the removal load were calculated using Eqs. (5) and (6). The dimension of concentration (Conc.) is in mg l^{-1} and that of flow rate is in m^3 d^{-1}.

$$\text{Received load} = \frac{\text{flow rate in} \times \text{Conc. in}}{\text{bed area}} \quad (5)$$

$$\text{Removed load} = \frac{(\text{flow rate in} \times \text{Conc. in}) - (\text{flow rate out} \times \text{Conc.out})}{\text{bed area}} \quad (6)$$

The removed CODs and TP loads were proportional to the received loads for all kinds of beds, whereas the T-N and NH_4–N removed loads were higher in the Vr beds than in V and H. Thus, recirculating the treated effluents resulted in enhanced removal of N in V flow wetlands mainly by a combination of nitrification and denitrification, in agreement with previous findings (Brix and Arias, 2005).

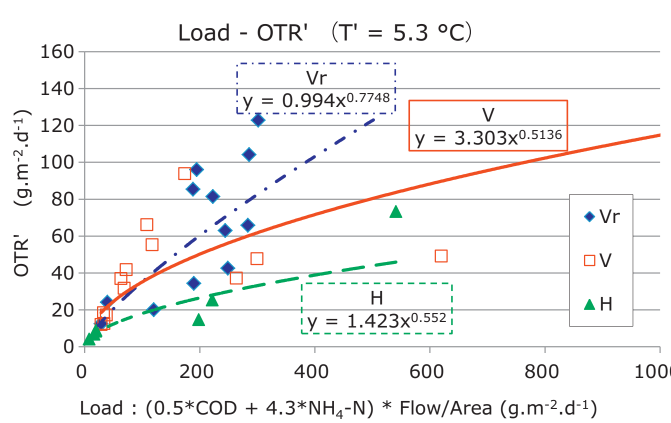

Fig. 5. Load of oxygen necessity (LON) and oxygen transfer rate (OTR′) values adjusted with mean air temperature.

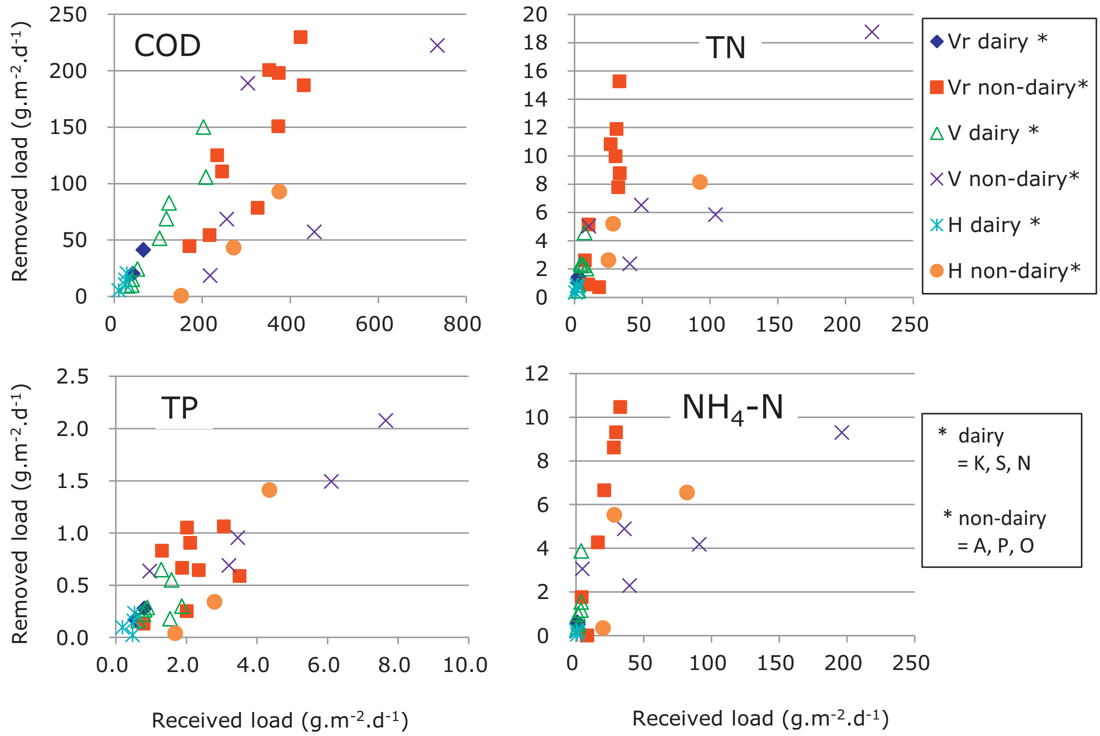

Fig. 6. Average received and removed loads in each bed.

4. Conclusion

The performance of six multi-stage hybrid wetland systems for treating high-content wastewater was evaluated in the cold climate of Hokkaido, northern Japan. A safety bypass structure and floating cover material was applied to the V flow bed to overcome clogging in the cold climate. The safety bypass structure and floating cover material helped prevent clogging and freezing, and maintained dry conditions, resulting in abundant reed and earthworm growth. The calculated average OTR increased in proportion to the influent load. The OTR was highest in V flow beds with a recirculating pump (Vr), medium in the V flow bed, and lowest in H flow beds. Recirculating the treated effluents was expected to enhance removal of nitrogen in V flow beds mainly by a combination of nitrification and denitrification. By treating higher organic loads per area without clogging, we could minimize the area required and cost of treating high-content wastewater. However, more data are needed concerning load and OTR to design a more efficient multi-stage wetland system.

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