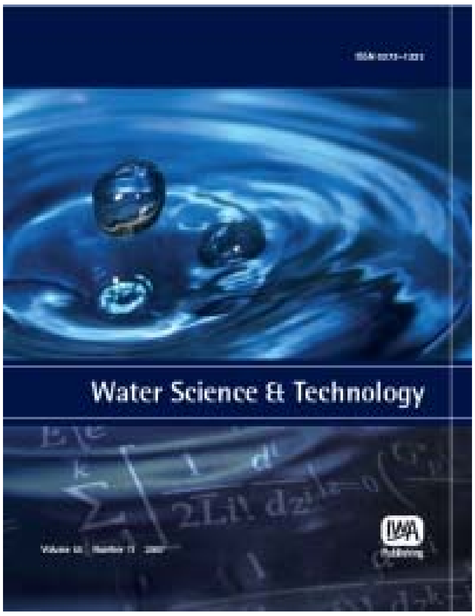
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Comparison of nitrogen elimination rates of different constructed wetland designs

Eriona Canga, Sara Dal Santo, Alexander Pressl, Maurizio Borin and Guenter Langergraber

ABSTRACT

In this paper the nitrogen elimination rates of different constructed wetland (CW) designs reported in literature are compared with those obtained for outdoor and indoor 2-stage vertical flow (VF) systems. The outdoor system is located about 150 km west of Vienna. Both stages are planted with *Phragmites australis* and the system has been operated for 4 years continuously. During this period the average value of the nitrogen elimination rate was 3.30 g N m^{-2} d^{-1}. The indoor system comprises three parallel operated 2-stage VF systems and is located in the technical lab hall at BOKU University. The design of the indoor system resembles the outdoor system. However, there are a few differences: (1) the indoor systems are not planted, and (2) different filter media have been used for the main layer of the first stages. With the indoor system the highest nitrogen elimination rate achieved was 2.24 g N m^{-2} d^{-1} for the system with zeolite and impounded drainage layer. Similar results have been found in France for treating raw wastewater with VF and horizontal flow (HF) beds in series with nitrogen elimination rates of 1.89 and 2.82 g N m^{-2} d^{-1} for differently designed HF beds. The highest nitrogen elimination rates of 15.9 g N m^{-2} d^{-1} reported were for pilot-scale VF CWs treating high-strength synthetic wastewater (total nitrogen of 305 mg L^{-1} in the influent) in Thailand. It has been shown that the outdoor two-stage VF CW system has one of the highest nitrogen elimination rates of CWs treating domestic wastewater.

Key words | constructed wetland design, nitrogen removal, two-stage vertical flow

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INTRODUCTION

Constructed wetlands (CWs) and in particular vertical flow (VF) CWs have become a popular technology for treating various types of wastewater especially for smaller treatment plant sizes. With VF systems usually good results regarding organic matter removal and nitrification can be achieved. However, they usually lack sufficient denitrification that is required for nitrogen removal (e.g. Vymazal 2007; Kadlec & Wallace 2009).

A two-stage VF CW system that was developed by Langergraber *et al.* (2008, 2010, 2011) guarantees full nitrification and allows high nitrogen elimination rates to be achieved. Dal Santo *et al.* (2010) describe modifications of the two-stage VF CW system that uses natural zeolite for the main layer of the first stage. The aim of this paper is to compare the nitrogen elimination rates measured for these two-stage VF systems with data from other designs found in literature to draw conclusions on optimal CW design for nitrogen removal.

MATERIAL AND METHODS

The two-stage VF systems

Table 1 summarizes the design of the different two-stage VF systems tested. The outdoor two-stage VF CW system (system 4) was constructed in 2005 and was designed with a specific surface area requirement of 2 m^2 per PE. The main layers of the two stages consist of sand with different gravel sizes, 2–3.2 mm and 0.06–4 mm for the first and second stages, respectively. The drainage layer of the first stage is impounded. Both stages are planted with *Phragmites australis*.

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Table 1 | Design of the indoor and the outdoor two-stage VF systems

		Stage 1		Stage 2		
System	Location	Main layer	Drainage	Main layer	Drainage	Vegetation
1	Indoor	Sand 1–4 mm	Impounded	Sand 0.06–4 mm	Free drainage	Unplanted
2	Indoor	Zeolite 2–5 mm	Impounded	Sand 0.06–4 mm	Free drainage	Unplanted
3	Indoor	Zeolite 2–5 mm	Free drainage	Sand 0.06–4 mm	Free drainage	Unplanted
4	Outdoor	Sand 2–3.2 mm	Impounded	Sand 0.06–4 mm	Free	*P. australis*

Data from June 2005 to July 2009 have been considered for the evaluation. More details on the outdoor system can be found in Langergraber *et al.* (2008, 2010, 2011).

The indoor two-stage VF systems (systems 1 to 3) have been described by Dal Santo *et al.* (2010). The design of the indoor system resembles the outdoor system. The differences are: (1) the indoor systems are not planted, and (2) different filter media have been used for the main layer of the first stages. Natural zeolite (gravel size 2–5 mm) has been used in 2 of the 3 systems whereas sand (gravel size 1–4 mm) was used in the remaining one. Data from May to July 2009 have been used for evaluation.

It is generally known that zeolite has a high adsorption capacity for ammonia. The main hypothesis for testing zeolite as the main layer of stage 1 was that low ammonium nitrogen concentrations can be already reached in the effluent of stage 1 thus resulting in less surface area requirement. Data supporting this hypothesis have been presented in Dal Santo *et al.* (2010).

Literature review

Journal papers as well as papers from proceedings of CW conferences have been used as sources. In particular all papers that allowed calculating TN loads and N elimination rates have been taken into consideration. In this paper only a selection of the papers is presented. The full data set is reported in Canga (2010).

RESULTS AND DISCUSSION

Data from literature

Data on N removal found in literature are summarized in Table 2. The systems are ranked according to increasing N elimination rate. For each system, data on the design, vegetation, hydraulic loading rate (HLR), organic and TN load, type of wastewater treated, etc. are given.

A correlation between TN influent loads and nitrogen elimination rates can be observed ($R^2 = 0.80$ for all systems in Table 2). The correlation is higher for single-stage VF systems ($R^2 = 0.95$) compared to single-stage horizontal flow (HF) systems ($R^2 = 0.74$). No correlation ($R^2 = 0.24$) can be found for the hybrid CW systems in Table 2 indicating that other factors determine the N elimination rate (e.g. design, different combination of HF and VF beds, etc.).

The two-stage VF CW systems

The data for the outdoor and indoor two-stage systems have been reported by Langergraber *et al.* (2010) and Dal Santo *et al.* (2010), respectively. In Table 2 the main data are summarised: The average nitrogen elimination rates obtained for systems 1 to 4 are 0.41, 2.24, 1.92 and 3.30 g N m^{-2} d^{-1}, respectively. The low N elimination rates of system 1 compared to system 4 (both with sand as a main layer of stage 1) indicate that the age of the system as well as the presence of plants contribute to increased N elimination. Langergraber *et al.* (2010) showed that the nitrogen elimination rates of the outdoor system increased (3.8 g N m^{-2} d^{-1}) and stabilized after the second year of operation. They concluded that the age of the system, in particular the development of plant roots and microbial biomass in the first stage, contributed to increased N removal of the system.

Comparison with single-stage VF systems for domestic and municipal wastewater

It can be observed that COD and TN influent loads of VF CWs are higher than those of HF CWs (usually HF CWs treat more diluted wastewaters). In agreement with Vymazal (2007), VF CWs remove more ammonia than HF CWs and FWS wetlands, due to high oxygenation of VF beds facilitated by intermittent loading of wastewater. However, the potential to denitrify is rather low and usually effluent nitrate concentration is high.

Table 2 | Summary of key data for various CW designs, ranking according to increasing N elimination rate (average values)

Reference	Type	Country	Surface area (total) (m^2)	Main layer: Material (–)	Main layer: Grain Size (mm)	Plants	HLR (mm d^{-1})	COD: Conc. IN (mg L^{-1})	COD: Load IN (g m^{-2} d^{-1})	Total Nitrogen: Conc. IN (mg L^{-1})	Total Nitrogen: Load IN (g m^{-2} d^{-1})	Total Nitrogen: Load OUT (g m^{-2} d^{-1})	Total Nitrogen: Load Elim. (g m^{-2} d^{-1})	Removal (%)	Wastewater
This study (System 1)	**VF+VF**	**Austria**	**2**	**Sand/sand**	**1–4/0–4**	**Unplanted**	**60**	**394**	**23.6**	**96**	**5.94**	**5.53**	**0.41**	**6.9**	**Municipal**
Sundblad (1998)	HF	Sweden	1,200	Gravel+ sand	n.a.	*P. australis*	36	n.a.	n.a.	39	1.40	0.90	**0.50**	35.9	Domestic
Zurita *et al.* (2009)	VF	Mexico	3.24	Tenzolte gravel	12	*Z. aethiopica/3 species*	40	248	9.8	29	1.13	0.57	**0.56**	49.6	Domestic
Zurita *et al.* (2009)	HF	Mexico	3.24	Tenzolte gravel	12	*Z. aethiopica/3 species*	40	248	9.8	29	1.13	0.52	**0.61**	53.7	Domestic
Senzia *et al.* (2003)	HF	Tanzania	15.9	Gravel	6–25	*P. mauritianus+ T. domingensis*	10	25*	2.7*	13	1.39	0.72	**0.67**	48.1	Domestic
Vymazal (2007), Table 3, $N = 85$	FWS	$N = 85$	–	–	–	–	–	–	–	–	1.28	0.60	**0.68**	53.0	–
Vymazal (2007), Table 3, $N = 113$	HF	$N = 113$	–	–	–	–	–	–	–	–	1.76	1.08	**0.68**	38.8	–
Senzia *et al.* (2003)	HF	Tanzania	40.7	Gravel	7–25	*P. mauritianus+ T. domingensis*	4.8	100*	4.9*	30	1.47	0.65	**0.82**	52.6	Domestic
Langergraber *et al.* (2007)	VF	Austria	17.8	Sand	0.06–4	*P. australis*	32	547	17.5	84	2.70	1.85	**0.85**	31.6	Municipal
Rivera *et al.* (1996)	HF	Mexico	600	Gravel	n.a.	*P. australis+T. latifolia*	58	1,401	81.7	124	7.25	6.34	**0.91**	12.5	High strength from abbatoir
Vymazal (2007), Table 3, $N = 14$	Free floating plants	$N = 14$	–	–	–	–	–	–	–	–	2.30	1.18	**1.12**	48.6	–
Luederitz *et al.* (2001)	HF	Germany	300	Sandy gravel	n.a.	*P. australis*	20	390	7.8	85	1.70	0.51	**1.19**	70.0	Municipal sewage
Langergraber *et al.* (2007)	VF	Austria	18.5	Sand	0.06–4	*P. australis*	43	547	23.4	84	3.62	2.32	**1.24**	34.4	Municipal
Laber *et al.* (1997)	VF	Austria	42	Sand+ gravel	0–8	*P. australis*	26	385	10.1	72	1.86	0.52	**1.34**	72.0	Domestic raw
Laber *et al.* (1997)	VF+VF	Austria	40	Sand+ gravel	1–4	*P. australis*	17	347	5.9	106	1.85	0.41	**1.44**	78.0	Domestic raw
Prochaska *et al.* (2007)	VF	Greece	0.24	Sand	0–4	*P. australis*	18	458	33.4	49	3.57	2.09	**1.48**	41.5	Simulated urban sewage

Liénard *et al.* (1998)	VF+VF	France	375	Gravel/ sand	n.a.	*P. australis*	77	495	38.3	46	3.55	1.97	**1.59**	44.6	Domestic sewage
Vymazal (2007), Table 3, *N* = 42	VF	*N* = 42	–	–	–	–	–	–	–	–	3.35	1.62	**1.73**	51.6	–
Pucci *et al.* (2004)	HF+VF+ HF+SF	Italy	6,080	Gravel/ sand	5–10/n.a	*P. australis*	86	280	24.2	35	3.03	1.29	**1.74**	57.4	Municipal
Molle *et al.* (2008)	VF+HF	France	66	Sand/sand	2–4/5–10	*P. australis*	60	412	24.7	59	3.10	1.21	**1.89**	61.0	Domestic raw
This study (System 3)	**VF+VF**	**Austria**	**2**	**Zeolite/ sand**	**2–5/0–4**	**Unplanted**	**60**	**394**	**23.6**	**96**	**5.95**	**4.03**	**1.92**	**32.2**	**Municipal**
Schulz *et al.* (2003)	HF	Germany	1.4	Sand	1–2	*P. australis*	5,140	30	151.9	2.0	10.20	8.09	**2.11**	20.6	(Extruded diet) trout effluent
This study (System 2)	**VF+VF**	**Austria**	**2**	**Zeolite/ sand**	**2–5/0–4**	**Unplanted**	**60**	**394**	**23.6**	**96**	**5.95**	**3.71**	**2.24**	**37.6**	**Municipal**
Luederitz *et al.* (2001)	VF	Germany	800	Sand/ gravel	0–4	*P. australis*	44	816	35.7	126	5.53	2.88	**2.65**	48.0	Municipal sewage
Luederitz *et al.* (2001)	VF	Germany	670	Sandy gravel	0–8	*P. australis+Juncus spp*	30	691	20.6	20	2.97	0.18	**2.79**	93.9	Municipal sewage
Molle *et al.* (2008)	VF+HF	France	66	Sand/sand	2–4/0–2	*P. australis+Juncus spp*	100	412	41.2	59	5.40	2.58	**2.82**	52.2	Domestic raw
Schulz *et al.* (2003)	HF	Germany	1.4	Sand	1–2	*P. australis*	5,140	41	210.9	2.4	12.30	9.07	**3.23**	26.2	(Pelleted diet) trout effluent
Gómez Cerezo *et al.* (2001)	SF+HF+VF	Spain	3	Sand/ gravel	0–2/12; 22	*P. australis; T. domingues*	192	449	86.2	46	8.83	5.57	**3.26**	37.1	Pretreated urban
This study (System 4)	**VF+VF**	**Austria**	**18.2**	**Sand/sand**	**2–3.2/0–4**	***P. australis***	**75**	**510**	**39.6**	**78**	**5.82**	**2.52**	**3.30**	**56.7**	**Municipal**
Sardón *et al.* (2006)	VF	Spain	288	Gravel	4–12; 3–8	Unplanted	51	1,033	52.2	103	5.33	1.82	**3.51**	65.9	Municipal
Gómez Cerezo *et al.* (2001)	IU+HF+VF	Spain	3	Sand/ gravel	1–2/12; 22	*P. australis; T. domingues*	372	449	167.0	46	17.16	13.11	**4.05**	23.6	Pretreated urban
Gómez Cerezo *et al.* (2001)	HF+HF+ VF	Spain	3	Sand/ gravel	1–2/12	*P. australis; T. domingues*	288	301	86.7	34	9.79	2.01	**7.78**	79.4	Lagoon effluent
Billore *et al.* (1999)	HF	India	41.8	Gravel	n.a.	*P. karka*	323	79*	25.4*	55	17.83	7.78	**10.0**	58.7	Municipal
Kantawanichkul *et al.* (2009)	VF	Thailand	0.2	Sand	1–2	*T. angustifolia*	50	275	13.8	305	15.26	5.01	**10.3**	67.2	High strength sintetic
Kantawanichkul *et al.* (2009)	VF	Thailand	0.2	Sand	1–2	Unplanted	80	275	22.0	305	24.42	12.46	**12.0**	49.0	High strength sintetic
Kantawanichkul *et al.* (2009)	VF	Thailand	0.2	Sand	1–2	*C. involucratus*	80	275	22.0	305	24.42	8.48	**15.9**	65.3	High strength sintetic

*BOD_5 instead of COD; n.a = not available; (/) separates two characteristics i.e., stage, material, grain size; N = number of investigated systems; HLR = hydraulic loading rate; FWS = free water surface flow; HF = horizontal flow; VF = vertical flow; IU = inverted up-flow.

Typical single-stage VF systems in Table 2 are the systems described by Zurita *et al.* (2009) and Langergraber *et al.* (2007) for which N elimination rates from 0.56 to 1.24 g N m^{-2} d^{-1} have been reported. According to Vymazal (2007) the average of N elimination rate and removal efficiency (in brackets) for 42 VF systems was 1.73 g N m^{-2} d^{-1} (51.6%) compared to 1.92 (32.2%), 2.24 (37.6%) and 3.30 g N m^{-2} d^{-1} (56.7%) for system 3, 2, and 4, respectively.

Laber *et al.* (1997) applied a recirculation rate of 80% of the effluent to the settling tank and used an impounded drainage layer. They obtained an N elimination rate of 1.34 g N m^{-2} d^{-1} and 72.0% removal efficiency. In terms of elimination rate, the Laber *et al.* (1997) study stayed below the results of the two-stage system described in this study, but in terms of % N removed the system had higher values. Other single-stage VF systems treating municipal wastewater for which high N elimination rates have been reported (e.g. Luederitz *et al.* 2001; Sardón *et al.* 2006), had rather high influent concentrations of organic matter and total nitrogen.

Comparison with single-stage HF systems for domestic and municipal wastewater

HF systems treating domestic wastewater (Sundblad 1998; Senzia *et al.* 2003; Vymazal 2007; Zurita *et al.* 2009) can be found in the upper part of Table 2, i.e., showing low N elimination rates (0.50–0.91 g N m^{-2} d^{-1}). The continuous loading of the HF beds and the water saturated conditions would principally favour denitrification. However, HF CWs have to be coupled with a nitrification stage in order to increase N removal. HF systems treating municipal wastewater had higher N elimination rates compared to HF treating domestic wastewater, mainly due to their high hydraulic loading rates, e.g. Billore *et al.* (1999) applied a hydraulic loading rate of 320 mm/d.

Compared to most of the single stage HF systems, the two-stage VF systems showed high N elimination rates. Only the CW described by Billore *et al.* (1999) showed a three-fold N elimination rate compared to the outdoor two-stage VF CW system (3.30 g N m^{-2} d^{-1}). However, the TN influent load was also about three-fold, again indicating the strong correlation between TN influent loads and nitrogen elimination rates.

Comparison with multi-stage systems for domestic and municipal wastewater

The results presented in Table 2 clearly indicate that single-stage CWs are not able to substantially remove N unless it is achieved at the expense of a large treatment area. Therefore hybrid systems may be a better solution when N removal is the main target value. The advantages of VF (high nitrification) and HF (high denitrification) can be combined to complement each other. Molle *et al.* (2008) combined VF (first stage) with HF (second stage) CWs in a full-scale experimental study. They tested two CW systems planted with *Phragmites australis* that had an identical VF bed as a first stage and differently designed HF beds for the second stage. Using a wide HF bed with fine filter media a high N elimination rate of 2.82 g N m^{-2} d^{-1} could be obtained; using a longer HF bed with coarse filter media only 1.89 g N m^{-2} d^{-1}. The N elimination rates of the systems described by Molle *et al.* (2008) are similar to those of the two-stage VF systems 2, 3 and 4 (outdoor and indoor with zeolite).

Laber *et al.* (1997) and Liénard *et al.* (1998) combined two VF beds operated in series planted with *Phragmites australis*. Laber *et al.* (1997) treated mechanically pre-treated wastewater whereas Liénard *et al.* (1998) raw sewage. An external carbon source was added to the second completely saturated VF bed by Laber *et al.* (1997). The N elimination rate of the system described by Liénard *et al.* (1998) was slightly higher than that of the system described by Laber *et al.* (1997) (1.59 and 1.44 g N m^{-2} d^{-1}), respectively), however, removal efficiencies have been higher for the system described by Laber *et al.* (1997). The lower elimination rates reported by Laber *et al.* (1997) were caused probably by the lower N load.

Other authors combined three stages (Gómez Cerezo *et al.* 2001) or four stages (Pucci *et al.* 2004). Gómez Cerezo *et al.* (2001) operated experimental three-stage CW systems whereby the surface area of each stage was 1 m^2. The first stage of the CW systems consisted of a surface flow, an inverted up-flow or a HF bed. All first stages were planted with *Phragmites australis*. The second stage of all systems was an HF bed planted with *Typha domenguensis* and the third stage a VF bed planted with *Phragmites australis*. The organic loads of the systems were high, i.e., 86.2, 167.0 and 86.7 g COD m^{-2} d^{-1} for the systems with the surface flow, inverted up-flow and HF bed as first stage, respectively; the obtained N elimination rates were 3.26, 4.05, and 7.78 g N m^{-2} d^{-1}, respectively. Pucci *et al.* (2004) obtained a lower N elimination rate of 1.74 g N m^{-2} d^{-1} by using a combination of an HF, VF, HF and SF bed for a full-scale CW system that was loaded with 24.2 g COD m^{-2} d^{-1}.

Comparison with CW systems treating other wastewaters

Rivera *et al.* (1996) described a system in Mexico treating high-strength wastewaters from an abattoir using an anaerobic digester for primary treatment and an HF CW planted with *Phragmites australis* and *Typha latifolia* for secondary treatment. The study evaluated the possibility of wastewater reuse for irrigation purposes. TN and COD influent concentration were 124 and 1,401 mg/L, with loading rates as high as 7.25 g N m^{-2} d^{-1} and 81.7 g COD m^{-2} d^{-1}, respectively. However, the N elimination rate was only 0.91 g N m^{-2} d^{-1} (12.5%), much lower than the removal rates of systems 2, 3 and 4.

Prochaska *et al.* (2007) investigated the performance of VF CWs for treating medium-strength synthetic urban sewage in a Mediterranean climate. The substrate used was river sand (0–4 mm) and the beds were planted with *Phragmites australis*. The wastewater was applied in batch volumes of 20 or 40 L over a surface of 0.24 m^2, for 2 or 3 times per week, for each wetland. The N elimination rate was typical for single-stage VF beds and was 1.48 g N m^{-2} d^{-1}.

Schulz *et al.* (2003) reported the treatment performance of three HF CWs planted with *Phragmites australis* for treating rainbow trout farm effluents. Three different loading rates of 1, 3 and 5 L/min (HRTs of 7.5, 2.5 and 1.5 hours, respectively) have been applied. The TN and COD concentrations (2.0–2.4 and 30–41 mg L^{-1}, respectively) in rainbow trout farms effluents are much lower than municipal wastewater. However, the maximum N elimination rate (as reported in Table 2) was high (3.23 g N m^{-2} d^{-1}) and was achieved due to the very high hydraulic loading of the system (HLR of 5 L/min, i.e. 5,140 mm/d).

Kantawanichkul *et al.* (2009) reported experiments under a tropical climate in Thailand treating high-strength synthetic wastewater with vegetated and unplanted pilot-scale VF CWs (surface area 0.2 m^2). The 0.2 m deep main layer consisted of sand (grain size 1–2 mm), the total height of the-filter columns was 0.6 m. Different hydraulic loads were applied (20, 50 and 80 mm d^{-1}) with a loading frequency of 30 min every 2 hours. Influent concentrations of COD and TN were 275 and 305 mg L^{-1}, respectively. The results indicated that VF CWs with unsaturated flow have a high capacity to treat high-strength wastewater in a tropical climate. N processing in the wetland was high, but not complete. As explained by the authors, the low bed depth and the substrate used (a matrix of coarse sand and gravel), did not allow a sufficient contact time between the wastewater and the filter medium to secure complete nitrification. They recommended a bed deeper than 0.6 m and finer material texture, being careful about the clogging potential effect. Due to the high TN influent concentrations, high N elimination rates could be achieved. These are the highest found in literature and ranged from 10.3 to 15.9 g N m^{-2} d^{-1} (for different settings).

SUMMARY AND CONCLUSIONS

The data in Table 2 can be summarized as follows:

1. CWs for wastewater treatment are usually highly loaded with N (ranging from 400 to 8,900 g N m^{-2} yr^{-1}) compared to natural wetlands (<10 g N m^{-2} yr^{-1}; Richardson 1990).
2. The N removal efficiency varied between 7 and 94% with N elimination rates ranging from 0.41 and 15.9 g N m^{-2} d^{-1}.
3. In general, for single-stage VF and HF CWs a strong correlation between TN influent load and N elimination rates can be observed.
4. In general, HF CWs show low N elimination rates ranging from 0.50 to 1.19 g N m^{-2} d^{-1}. Higher N elimination rates were attributed predominantly to VF CWs and multi-stage CWs.
5. The two-stage VF systems presented had high N elimination rates (except system 1, the unplanted indoor system with sand). Of the unplanted indoor systems, system 2, the system with zeolite and impounded drainage layer in the first stage, performed best.

Regarding optimal design of CWs for N removal, the following conclusions can be drawn:

- High N elimination rates can not be achieved with HF beds alone. This is due to deficiency of nitrification in HF CWs. Also single-stage VF beds can not achieve high N elimination rates due to the lack of environmental conditions favouring denitrification. In hybrid CWs where HF and VF beds are combined, high N removal can be achieved.
- For domestic/municipal wastewater the outdoor two-stage VF CW system had one of the highest N elimination rates (3.30 g N m^{-2} d^{-1}). The two-stage VF design is therefore suitable for achieving high N elimination rates when also full nitrification is required. It can be assumed that vegetation and longer operation time, in particular the development of plant roots and microbial biomass

in the subsurface, influence N removal efficiency of the system (Langergraber *et al*. 2011).

- A similar N elimination rates as for the two-stage VF systems was reported for a combination of VF and HF beds for treating raw wastewater (1.89 to 2.82 g N m^{-2} d^{-1}) by Molle *et al*. (2008).
- Higher N elimination rates were achieved only with CW systems
  1. treating high strength wastewater (e.g. Kantawanichkul *et al*. (2009), influent TN > 300 mg L^{-1}, or Sardón *et al*. (2006), with influent COD > 1,000 mg L^{-1} and influent TN > 100 mg L^{-1}),
  2. having high organic loads (e.g. Goméz Cerezo *et al*. (2001), influent COD loads from 86–167 g m^{-2} d^{-1}) and/or
  3. having very high hydraulic loading rates (e.g. Billore *et al*. (1999), Goméz Cerezo *et al*. (2001), with 192–372 mm d^{-1}; and Schulz *et al*. (2003), with up to 5,140 mm d^{-1}, respectively).

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