

The effects of flow regime and temperature on the wastewater purification efficiency of a pilot hybrid constructed wetland

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Abstract

A pilot scale experimental hybrid constructed wetland (CW) was established in 2005 for the treatment of mixed effluents from municipal sources and food processing plants in a small village in southern Estonia. The aim was to find optimal operating regimes (varying hydraulic loading rates, loading intervals, recirculation regimes and regimes of hydraulic retention time) for the use of analogous CWs in cold climates. The hybrid wetland system consists of two parallel systems designed on the same principle: a vertical subsurface flow (VSSF) filter followed by a horizontal subsurface flow (HSSF) filter. The VSSF filter of one system (the left filter) is filled with crushed limestone, while the other (right) is filled with light weight aggregates (LWA). Both HSSF filters are filled with LWA. From December 2005 until December 2006, water samples from the outlet of the septic tank and the outlet of both VSSF and HSSF filters were taken once a week. In both systems, a combination of decreasing hydraulic load (from 52 to 14 mm d⁻¹) and increasing recirculation rate (from 34 to 300%) caused a significant increase in the purification efficiency of BOD₇ (from 58 to 99%), N_{tot} (from 11 to 82%), and NH₄-N (from -16 to 83%). In both systems, the removal efficiency of P_{tot} did not show any significant correlation with hydraulic load, whereas in the right (LWA) system, the increasing recirculation rate significantly increased P_{tot} removal. The dynamics of the COD value was analogous to that of the BOD₇ value, but no significant differences were found between the removal efficiency of total suspended solids (TSS) of different flow regimes. Likewise, water temperature did not show a significant correlation between the purification efficiency of all of the studied water quality indicators. For the successful functioning of hybrid CWs in a cold climate, optimal hydraulic load should be ≤20 mm d⁻¹ with a recirculation rate of 150-300%.

Keywords: aeration, design, hybrid constructed wetland, limestone, LWA, recirculation.



1 Introduction

Constructed wetlands (CW) of various types are becoming popular worldwide [1]. In addition to their satisfactory performance, multifunctionality in terms of biodiversity and landscape services, and cost-effectiveness, CWs have one significant disadvantage: high area requirement [2]. The idea of compact systems is to sustain systems with lower area requirement and lower building costs. In cold climates, CWs are often designed with a reserve in order to compensate for lower temperatures during winter [3–5]. Providing measures that can help achieve proper results without over-dimensioning would make CW a much more attractive wastewater treatment technology. One possible operational method to compensate for their small area and short retention time is to recirculate the wastewater. As the effluent is being re-circulated, additional oxygen for aerobic microbial activities can be transferred into the wastewater. In addition, as the suspended solids are predominantly removed by filtration, recirculating the effluent increases the chances for the suspended solids to be trapped in the system [6]. These factors should account for the improvement of overall purification processes.

Hydraulic loading and hydrologic detention time are key factors of purification efficiency in all types of constructed wetlands [1]. Excessively high hydraulic load has been reported as a main limiting factor of purification processes in both subsurface flow wetland systems [7, 8] and free water surface wetlands (FWSW [9, 10]). The recirculation of treated effluent from CWs as a procedure enhancing aeration and purification processes has been used in various laboratory experiments and pilot- and full-scale CW systems [11]. Several studies have been carried out in VSSF filters of tidal flow for the treatment of municipal wastewater [12–14] and piggery wastewater [11, 15]. Also, in downflow regime VSSF filters of 1-stage [16–18], 2-stage [19], and 3-stage [20], HSSF filters [21], and hybrid (combined from VSSF and HSSF filters) CWs [22–24] treating domestic and farm effluents, recirculation has been successfully used. Likewise, recirculation has significantly enhanced the purification of landfill leachates [25, 26]. Of water quality indicators, the values of BOD and COD [14, 15, 18, 20, 21], and concentrations of N_{tot} [11, 17, 22, 23], $NH_4\text{-N}$ [11, 14, 15, 18–20], P_{tot} [13, 14], total suspended solids (TSS [14, 18]), and polyphenols [21] have been reduced. Several studies report enhanced aeration and increased O_2 consumption by microorganisms [12, 20, 24]. On the other hand, there are studies that point out no significant influence of recirculation on the removal of P_{tot} [18, 27], $NH_4\text{-N}$ [16, 28], and indicator bacteria (total and faecal coliforms, faecal streptococci [29]). However, in some countries the recirculation of wastewater in subsurface flow filters has been included in the official guidelines on CWs [16, 27].

Temperature is another key factor controlling purification processes in CWs [1]. However, the influence of temperature in full-scale treatment wetlands and pilot systems demonstrates temperature effects that differ from the results acquired at the laboratory-scale or by modelling. The majority of studies show that in FWSWs, all the purification processes slow down significantly with



decreasing temperature [30–34], whereas in some cases the export of nutrients (P_{tot}) from wetlands in winter has been observed [33]. Some authors report that the P retention and mineralization of organic matter (based on BOD value) are the less temperature-affected processes in FWSWs [34], and in some specific cases no differences in the removal of BOD, TSS, $\text{NH}_4\text{-N}$ and P_{tot} between the warm and cold period were found [35, 36].

Various subsurface flow CWs show a much more diverse pattern of temperature effects on purification processes. The LWA-or Filtralite-P-based hybrid CWs combined from VSSF and HSSF filters in series and treating domestic wastewater show equally high long-term efficiency in both summer and winter [3, 37–40]. Likewise, hybrid subsurface flow CWs used for landfill leachate treatment [41], as well as single or 2-stage VSSF and HSSF filters treating municipal effluents [42, 43] show equally high performance in summer and winter. In contrast, some studies report lower $\text{NH}_4\text{-N}$ and P removal in subsurface flow wetlands in winter [44, 45], whereas Kuschik et al. [46] report on a significantly lower N removal in an experimental HSSF in the winter season.

The main objective of this study is to determine optimal loading and operational regimes for LWA-based and Limestone-LWA based two-stage hybrid wetland systems in cold climate conditions for the treatment of municipal and agro-industrial wastewater. This paper presents the purification efficiencies during different hydraulic loadings and recirculation regimes and analyses these results against the background of critical factors for water purification.

2 Material and methods

2.1 Site description

The Nõo experimental CW is located on the territory of the active sludge wastewater treatment plant (AWP) of Nõo village. The wastewater (domestic wastewater combined with dairy and meat industry wastewater) is pumped into the CW before it reaches the grid of the AWP. The exact water volume is controlled by a timer-operated pump. A certain amount of wastewater is first pumped into a septic tank (2 m^3). After the septic tank, the wastewater is divided equally between both parallel experimental systems (area of both VSSF filters: $2 \times 4 \text{ m}^2$; area of both HSSF filters: $2 \times 10 \text{ m}^2$) (Fig. 1).

The pilot scale hybrid CW in Nõo consists of two analogous systems with different operating regimes designed on the same principle: a vertical subsurface flow (VSSF) filter 0.7 m in depth followed by a horizontal subsurface flow (HSSF) filter 1 m in depth. The filters were covered (air temperatures fell to -35°C) with 5 cm thick insulation slabs during winter. The systems were not initially planted. During the vegetation period, plant cover developed spontaneously on the VSSF part of both systems.

Table 1 reports the cross-section of VSSF filters, constructed such that the bottom layer has the highest and the upper layer the lowest hydraulic conductivity. Both HSSF filters are filled with light weight aggregates (LWA) with particle size 2–4 mm.



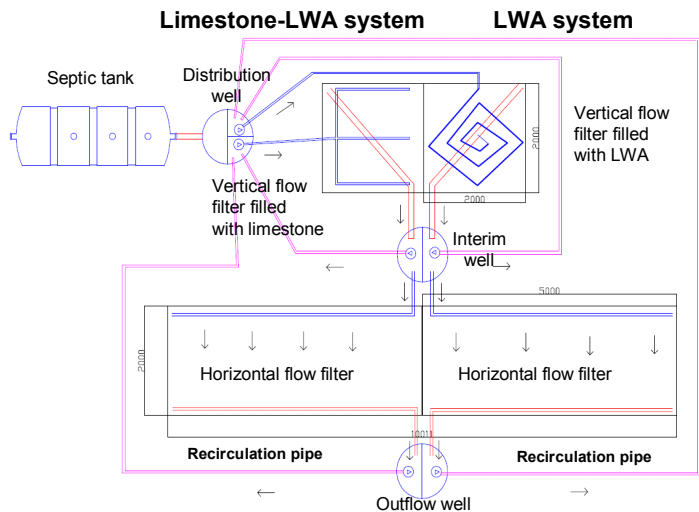


Figure 1: Schematic layout of the experimental pilot system of the hybrid constructed wetland in Nõo, Estonia.

Table 1: Cross-sections of vertical flow filters.

Layers	Right bed	Left bed
Upper layer (20 cm)	crushed limestone Ø 2-8 mm	LWA Ø 2-4 mm
Middle layer (20 cm)	crushed limestone Ø 8-16 mm	LWA Ø 4-10 mm
Bottom layer (25 cm)	crushed limestone Ø 12-32 mm	LWA Ø 10-20 mm

2.2 Operational regimes of hybrid constructed wetland system

There was a possibility to recirculate wastewater from the outflow well of the VSSF filters (interim well), as well as from the outflow of the HSSF filters (outflow well; Fig. 1) using timer-controlled pumps.

This paper covers 6 different operational regimes that were applied simultaneously to both parallel systems. The degree of recirculation was enhanced during the sequential operational regimes, but was not equal for the parallel systems (Table 2).

2.3 Water sampling and analysis

Water samples were taken from 07.12.05 to 20.12.06 once a week simultaneously from both systems, from the outlet of the septic tank and the outlet of both VSSF and HSSF filters. The number of water samples per operational regime (1-6) varied in the following order: 1st – 4 samples, 2nd – 11 samples, 3rd, 4th and 5th – 9 samples each, and 6th – 11 samples. In the laboratory of the AS Tartu Veevärk, water samples were analyzed for BOD₇, TSS, COD, N_{tot}, NH₄-N, NO₂-N, NO₃-N, P_{tot} using Standard Methods for the Examination of Water and Wastewater [47].



Table 2: Operational regimes and respective recirculating regimes (% from hydraulic loading rate), hydraulic loading rates and average wastewater temperatures in the Nõo hybrid constructed wetland system.

Operational regime	Recirculating regimes of studied systems*				Hydr. loading rate m ³ d ⁻¹	Average water temp. (°C)	
	LWA		Limestone-LWA			Inflow	Out-flow
	From interim well %	From outflow well %	From interim well %	From outflow well %			
1	0	34	0	24	0.73	6.5	5.2
2	0	34	0	25	0.37	3.9	1.5
3	48	0	73	0	0.29	7.4	6.2
4	0	250	250	0	0.22	16.4	17.8
5	0	300	150	150	0.3	16.9	16.1
6	150	150	0	300	0.2	8.3	7.2

* summarized recirculation rates from outflow and interim well were used in correlation analysis.

2.4 Statistical analysis

This paper presents data and compares the purification efficiencies of 6 different operational regimes in the limestone-LWA and 6 different operational regimes in the LWA experimental systems. All parameters were controlled for normality (Kolmogorov-Smirnov, Lilliefors' and Shapiro-Wilk's tests). The differences between the purification efficiencies of operational regimes were analysed using Kruskal-Wallis ANOVA. The Mann-Whitney test was used for the comparison of purification efficiencies, and in the case of nitrites and nitrates, for the comparison of the values of the inflow/outflow concentration ratios of the sequential operational regimes. Pearson correlation coefficients were detected between influencing factors and purification efficiencies of BOD_7 , N_{tot} , $\text{NH}_4\text{-N}$ and P_{tot} . We used *Statistica 7.0* for data analysis.

3 Results and discussion

3.1 Inflow concentrations

The inflow concentrations of the studied water quality indicators were typical of the ordinary municipal wastewater, except for COD, which was somewhat higher than in ordinary municipal wastewater [1]. This could be related to the inflow of high concentrations of chemicals used in the local meat and dairy industry (see Table 3).

3.2 Average purification of organic pollutants, suspended solids and nutrients

The analysis of the differences of the experimental cycles by Kruskal-Wallis ANOVA revealed that all studied indicators of the LWA-side (left side) of the CW, except for TSS, showed significant differences between the cycles



($p < 0.01$). The Limestone-LWA side (right side) also showed significant differences for all studied indicators (for BOD_7 , COD, N_{tot} , NH_4-N , $p < 0.01$; P_{tot} , NO_2-N and NO_3-N , $p < 0.05$), except for TSS.

Table 3: Average and standard deviation values of the concentrations ($mg\ L^{-1}$) of studied water quality parameters in the inflow of the studied hybrid constructed wetland system during sequential operational regimes (the header of the columns is indicated by numbers).

Water quality parameter	1	2	3	4	5	6
BOD_7	405±135	413±66	446±216	644±138	640±159	375±75
TSS	132±17	116±36	219±192	287±154	387±396	117±19
COD	690±133	745±120	808±519	1076±369	1135±533	590±59
N_{tot}	65±6	72±22	54±18	91±33	112±33	78±10
NH_4-N	50±11	52±16	47±14	77±39	80±33	62±11
NO_2-N	0.013 ±0.002	0.001 ± 0.0003	0.168 ± 0.22	0.019 ± 0.03	0.013 ± 0.02	0.006 ± 0.003
NO_3-N	0.42 ±0.16	0.12 ±0.1	0.03 ±0	0.41 ±0.35	0.6 ±0.2	0.4 ±0.1
P_{tot}	20±3	21±4	20±8	31±9	44±15	26±5

The lack of significant differences in the purification efficiency of TSS between the cycles is probably related to the relatively high variability of the sedimentation rates of different size fractions of TSS compared to the variability of the sedimentation conditions, such as flow rate during different experimental cycles, and also to the compensating effects of the different stages of wastewater purification. For example, while recirculation decreases sedimentation due to the enhanced speed of the water flow inside the HSSF, this may be compensated by higher oxidation of TSS in the VSSF.

3.3 The comparison of the studied water quality indicators during the sequential operational regimes

The comparison of the purification efficiency of BOD_7 , N_{tot} , NH_4-N , and P_{tot} between the sequential operational regimes in both LWA and Limestone-LWA systems during the experiment period (Mann-Whitney tests) showed general growth trends for all studied parameters, except for P_{tot} in the Limestone-LWA system (Fig. 2).



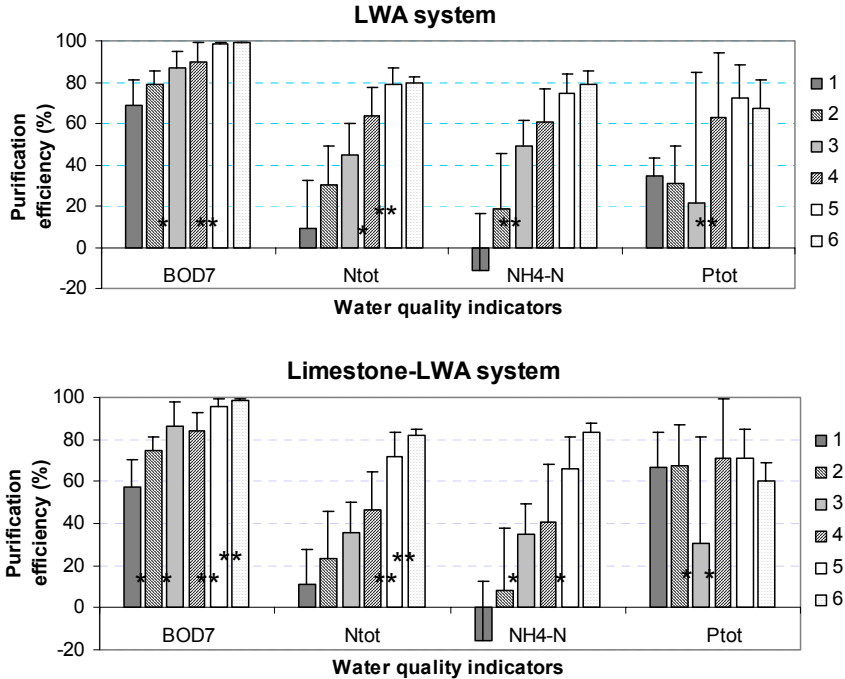


Figure 2: Average values and standard deviation (bars) of purification efficiency of BOD₇, N_{tot}, NH₄-N and P_{tot}, (%) in both LWA and Limestone-LWA system beds during various operational regimes (1-6; see Table 2). Asterisks indicate significant differences (Mann-Whitney test) between neighbouring operational regimes: * - $p < 0.05$, ** - $p < 0.01$.

The LWA system could remove up to 99% BOD, 81% N_{tot}, 79% NH₄-N, and 67% P_{tot}, whereas in the Limestone-LWA system these values were 99, 82, 83 and 60% respectively (Fig. 2).

3.3.1 LWA system

The growth of the removal efficiency of BOD₇ (Fig. 2) in the 3rd operational regime compared to the 2nd operational regime could be caused by the enhanced recirculation rate, decreasing rates of wastewater inflow to the CW, and also by increasing water temperature due to seasonal changes. However, growth in the 5th operational regime compared to the 4th operational regime was obviously caused by enhanced recirculation, which could have a crucial effect on relief of oxygen deficit due to higher water temperatures.

N_{tot} removal efficiency showed an increasing trend throughout the study period, and thus the purification processes of N_{tot} were influenced by recirculation, which enables sufficient aeration for the degradation of organic N and oxidation of ammonia. Significant growth of the purification efficiency of

NH₄-N in the 3rd operational period compared to the 2nd operational period that occurred in the relatively colder season was probably caused by higher oxygen solubility in lower temperatures, indicating a lower temperature optimum for nitrification compared to denitrification. The significant growth of P_{tot} after the steep enhancing of the recirculation rate in the 4th operational regime compared to the 3rd operational regime indicates that the processes of P retention in the LWA system were supported by enhanced aeration [1].

3.3.2 Limestone – LWA system

The comparison of the purification efficiency of BOD₇ between the sequential operational regimes showed additional significant differences between the operational regimes compared with the LWA system (Fig. 2). These differences in the systems could be caused by the relatively poor properties of limestone compared to LWA in terms of aeration and insulation, which enhance the effects of other factors such as hydraulic loading rate and temperature regime. The same is obviously valid for N_{tot} and NH₄-N, which also gave some additional significant differences between operational regimes compared with the LWA system. The purification efficiency of P_{tot} during the first two operational regimes was nearly twice as higher in the limestone-LWA system than in the LWA system, which could be related to the higher P retention capacities of CaCO₃-rich limestone. The significantly lower purification efficiency of P_{tot} during the 3rd operational regime compared to the preceding and following operational regime probably reflects the influence of the lower water temperature and the switching of the recirculation from the outflow well to the interim well. This could have an effect on the reaction balances in the vertical filter, because enhanced inflow of O₂-rich water from the interim well may suppress the solubility of CO₂. Thus the average CO₂ concentration could become the limiting factor in the geochemical pathway that leads to the final sedimentation of P.

3.4 The changes in the inflow/outflow concentration ratio for nitrites and nitrates during sequential operational regimes

The inflow/outflow concentration ratio of NO₂-N was significantly lower in both systems during the 1st operational regime compared to the 2nd operational regime. The comparison of the latter cycles did not reveal significant changes in the production of NO₂-N (Table 4). These commonalities are probably related to the initial phases of the development of a nitrifying microbial community. The initial phases of nitrification – nitrite production – was not limited by NH₄-N availability. The next phase of nitrification, nitrate production – is limited by the production of nitrite, and thus the community of nitrite producers should be developing faster and should be located closer to the inflowing resource, NH₄, especially in the case of diffusion-limited mass transport processes in the wetland substrate, which is discussed in greater detail by Austin et al. [48]. We suggest that this situation should gradually change towards complete nitrification, especially when high recirculation rates are applied.

Significant growth of the inflow/outflow concentration ratio of NO₃-N in the 6th operational regime compared to the 5th operational regime in the LWA system



is probably caused by the enhanced oxygen solubility due to the lowered wastewater temperature in the autumn. LWA-based vertical filter has a better ability to enrich the water with oxygen, and thus the effect of lowered temperature could also have a stronger effect on nitrification. The lower inflow/outflow concentration ratio of $\text{NO}_3\text{-N}$ in the Limestone-LWA system during the 4th operational regime compared to the 3rd operational regime could also be caused by enhanced wastewater temperature in the 4th operational regime, which lowers the solubility of O_2 (Table 4).

Table 4: Average (aver) and standard deviation (stdev) values of the inflow/outflow concentration ratio for nitrites and nitrates in both LWA and limestone beds. << indicates significantly differing values between the neighbouring operational regimes (Mann-Whitney test, $p < 0.01$).

Cycles		1	2	3	4	5	6
NO_2 aver	LWA	0.23 <<	79.6	26.3	43.5	26.6	18.9
	stdev	0.31	158.5	50.8	65.2	43.3	27.4
NO_2 aver	limestone	0.29 <<	1.06	6.11	19.6	19.5	22.3
	stdev	0.29	0.39	16.5	29.4	19.3	28.0
NO_3 aver	LWA	0.54	1.05	1.00	3.03	0.92 <<	2.2
	stdev	0.40	0.51	0.00	5.13	1.14	1.4
NO_3 aver	limestone	0.46	0.90	1.00 <<	0.68	0.99	1.8
	stdev	0.30	0.33	0.00	0.25	0.62	1.1

3.5 Impact of temperature and flow regimes

Pearson correlation coefficients between the purification efficiency of BOD_7 , N_{tot} , $\text{NH}_4\text{-N}$, P_{tot} and the main regulators of wastewater purification efficiency (hydraulic load, recycling regime, wastewater temperature) were detected.

3.5.1 Impact of water temperature

Wastewater temperature in the inflow and outflow had no significant correlations with the purification efficiency of BOD_7 , N_{tot} , $\text{NH}_4\text{-N}$ and P_{tot} . There were only weak positive relationships below the accepted level of significance, and R^2 varied between 0.10 and 0.58. This situation seems to be typical to CW-s due to the trade-off between the effects of temperature-sensitive factors such as O_2 solubility in the water and (bio)chemical reaction rates.

3.5.2 Impact of hydraulic load and recirculation regime

The most influential factor for wastewater purification efficiency was the wastewater recirculation regime.

In the LWA system, recirculation regime had highly significant positive correlations with the purification efficiency of N_{tot} ($p < 0.01$, $R^2 = 0.85$), $\text{NH}_4\text{-N}$



($p < 0.01$, $R^2 = 0.94$), P_{tot} ($p < 0.01$, $R^2 = 0.94$) and a significant correlation with BOD_7 removal efficiency ($p < 0.05$, $R^2 = 0.76$), whereas hydraulic load was negatively correlated with BOD_7 ($p < 0.05$, $R^2 = 0.74$) and N_{tot} purification efficiency ($p < 0.05$, $R^2 = 0.71$), and $\text{NH}_4\text{-N}$ had a non-significant tendency towards a negative relationship with hydraulic load ($p = 0.07$, $R^2 = 0.59$).

The more significant effect of the recirculation regime on the purification efficiencies of N-compounds is consistent with general knowledge about environmental needs for nitrogen processing pathways. A significant correlation between recirculation regime and P purification efficiency could be explained by the redox-sensitivity of the Fe and Al reactions of P, which is transformed into stable, non-soluble form in aerobic conditions, and into soluble form in anaerobic conditions [1].

The Limestone-LWA system also showed a highly significant positive correlation between recirculation rate and N_{tot} ($p < 0.01$, $R^2 = 0.86$), and significant positive correlations of recirculation rate with $\text{NH}_4\text{-N}$ ($p < 0.05$, $R^2 = 0.81$) and BOD_7 purification efficiency ($p < 0.05$, $R^2 = 0.87$), but lacked a correlation of recirculation rate with P_{tot} purification efficiency ($p = 0.56$, $R^2 = 0.09$), whereas hydraulic load was negatively correlated with BOD_7 ($p < 0.05$, $R^2 = 0.79$) and $\text{NH}_4\text{-N}$ purification efficiency ($p < 0.05$, $R^2 = 0.71$), and had a non-significant tendency of a negative relationship between hydraulic load and N_{tot} purification efficiency ($p = 0.093$, $R^2 = 0.55$). The absence of a positive correlation for P_{tot} purification efficiency and recirculation regime in this system could be related to the previously described mechanism that depends on dissolved CO_2 (see section 3.3.2), does not depend on the redox potential in the filter media and therefore is not influenced by the recirculation rate.

The lack of correlation between the hydraulic loading rate and P_{tot} purification efficiencies in both systems indicates that P transformation and subsequent retention in the CW was not limited by the diffusion rates of P compounds and was controlled by the reaction rates at specific steps of P transformation. The stronger correlation of $\text{NH}_4\text{-N}$ purification efficiency and recirculation regime in the LWA system than in the Limestone-LWA system shows that $\text{NH}_4\text{-N}$ purification processes in the LWA system were more sensitive to additional aeration than in the limestone LWA system, which could be explained by the greater specific area of the LWA-based vertical filter.

Our results suggest that optimal hydraulic load for the hybrid CWs in cold climates should be up to 20 mm d^{-1} with a recirculation rate of 150-300%. This is coherent with the data in the literature. In milder climatic conditions higher hydraulic loadings can be optimal [8] and also 100-200% recycling rate can give 52-65% N_{tot} removal [17] and even 65-70% $\text{NH}_4\text{-N}$ removal with a detention time of only 3.5 days [19]. In tropical regions already 50% recirculation guarantees increase in $\text{NH}_4\text{-N}$ removal from 71 to 85% [22]. In cold climate regions a recirculation rate up to 150% can increase the removal of BOD, and $\text{NH}_4\text{-N}$ up to 81 and 62% respectively [18]. Thanks to the higher recirculation rate, the results of our study were higher (Fig. 2).



4 Conclusions

Purification efficiencies of BOD_7 , N_{tot} and NH_4-N responded negatively to the increases in hydraulic loading rates, and positively to the enhancing of recirculation rate, whereas the purification efficiency of P_{tot} only showed a positive response to enhanced recirculation rate in the LWA system, and was not affected by the changes in the hydraulic loading rates.

The purification efficiency of the studied indicators did not depend on the wastewater temperature. The overall production of NO_2 throughout the studied operational regimes in both systems shows that CWs were in the state of the initial phase of the development of a nitrifying microbial community.

The removal efficiency of BOD_7 depends equally on the enhancing of the recirculation rate and the lowering of the hydraulic loading rates, whereas purification efficiencies of N compounds were related to the increase in recirculation.

Thanks to the higher specific area of the filter material, the LWA system showed somewhat higher sensitivity of N removal to increased recirculation rate than the Limestone-LWA system.

The fact that the purification efficiency of the P_{tot} in the Limestone-LWA system was somewhat higher than in the LWA system and did not depend on recirculation rates as in the LWA system indicates the different mechanisms of P retention were predominant in different systems. The Limestone-LWA system probably retained P through sedimentation reactions with Ca, whereas the LWA system retained P in redox-potential dependent reactions of P with soil Fe and Al.

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