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Review

Constructed Wetlands for Agricultural Wastewater Treatment in Northeastern North America: A Review

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Abstract: Constructed wetlands (CW) are a treatment option for agricultural wastewater. Their ability to adequately function in cold climates continues to be evaluated as they are biologically active systems that depend on microbial and plant activity. In order to assess their performance and to highlight regional specific design considerations, a review of CWs in Eastern Canada and the Northeastern USA was conducted. Here, we synthesize performance data from 21 studies, in which 25 full-scale wetlands were assessed. Where possible, data were separated seasonally to evaluate the climatic effects on treatment performance. The wastewater parameters considered were five-day biochemical oxygen demand (BOD_5), total suspended solids (TSS), *E. coli*, fecal coliforms, total Kjeldahl nitrogen (TKN), ammonia/ammonium (NH_3/NH_4^+-N), nitrate-nitrogen (NO_3^--N), and total phosphorus (TP). Average concentration reductions were: BOD_5 81%, TSS 83%, TKN 75%, NH_4^+-N 76%, NO_3^--N 42%, and TP 64%. Average log reductions for *E. coli* and fecal coliforms were 1.63 and 1.93, respectively. Average first order areal rate constants (k_a, $m \cdot y^{-1}$) were: BOD_5 6.0 $m \cdot y^{-1}$, TSS 7.7 $m \cdot y^{-1}$, *E. coli* 7.0 $m \cdot y^{-1}$, fecal coliforms 9.7 $m \cdot y^{-1}$, TKN 3.1 $m \cdot y^{-1}$, NH_4^+-N 3.3 $m \cdot y^{-1}$, NO_3^--N 2.5 $m \cdot y^{-1}$, and TP 2.9 $m \cdot y^{-1}$. In general, CWs effectively treated a variety of agricultural wastewaters, regardless of season.

Keywords: agricultural wastewater; cold climate; constructed wetlands; water treatment

1. Introduction

As constructed wetland (CW) systems gain increasing acceptance as wastewater treatment technologies, a need exists for information about their design, operation and performance [1–3]. There are many applications for CWs ranging from the treatment of landfill leachate, domestic sewage, to the management of agricultural wastewater. It is important to consolidate the knowledge and experience gained from the many CW studies that have been conducted and summarize the regional performance and wastewater source data. Literature reviews [4–7], factsheets (e.g., [8]) and databases [1,9,10] are available for various regions and wastewater types, but, presently, a review of CW performance treating agricultural wastewater and wash water in northeastern North America does not exist. The purpose of this review is to consolidate CW research and assess their performance for agricultural applications in this region.

The climate of northeastern North America is classified as humid continental (Dfb) according to the Köppen–Geiger classification system, and the region experiences warm summers and cold winters with precipitation generally uniformly distributed throughout the year [11]. The average temperatures of Augusta, ME, Toronto, ON, and Halifax, NS, three cities in this region, are 20.8, 22.0, and 18.8 °C, respectively, for the warmest month, July, and −4.7, −2.6, and −3.6 °C, respectively, for the coldest month, February [12–14]. The most common agricultural systems in northeastern North America are cash crops including grains and oilseeds and beef and dairy production [15–17]. Runoff from crop fields, barnyards and feedlots and the discharge of contaminated process water can introduce significant amounts of unwanted nutrients and other pollutants into the environment if it is not captured and properly treated [18].

CWs are a relatively inexpensive and low-maintenance option for agricultural applications and are capable of treating a number of wastewater types [1,3]. Applications include the treatment of milkhouse wash water and farmyard runoff [19–27], tile drainage outflow [28–31]), aquaculture wastewater [32,33] abattoir wastewater [34], and winery process water [35]. CWs are engineered to optimize naturally occurring biological, chemical, and physical processes to treat wastewaters. However, many of these processes can be affected by temperature and as a result questions have been raised about CW ability to function year-round in cold regions.

This paper synthesizes the literature and available performance data of CWs treating agricultural wastewater in northeastern North America. The parameters included were five-day biochemical oxygen demand (BOD_5), total suspended solids (TSS), *E. coli*, fecal coliforms, total Kjeldahl nitrogen (TKN), ammonia+ammonium-N (NH_3+NH_4^+-N), nitrate-nitrogen (NO_3^--N), and total phosphorus (TP). The average performance data of the reviewed studies are presented in Tables 1 and 2 and a summary of the performance categorized by wetland design and season are shown in Table 3. The literature summarized was primarily peer reviewed published sources as well as graduate student dissertations. In some cases, however, when a source was brief (e.g., a conference abstract) unpublished data were requested from the authors. The geographic range was the province of Ontario and eastward in Canada and the New England states. This was intended to cover a region with a similar climate and comparable agricultural activities. Generally, indoor and laboratory experiments were not included in this review.

Table 1. Mean influent and effluent concentrations, concentration reductions (CR, %), and areal adjusted rate constants (k_a, y^{-1}) for five-day biochemical oxygen demand (BOD_5) and total suspended solids (TSS). Mean log reductions (LR) for *E. coli*, and fecal coliforms.

Study	Prov./State[a]	CW Type	Area (m^2)	Waste Water Source	Study Length (mo)	BOD_5 (mg L^{-1})				TSS (mg L^{-1})				*E. coli* (CFU/100 mL)				Fecal Coliforms (CFU/100 mL)			
						in	out	CR %	k_a	in	out	CR %	k_a	In	out	LR	k_a	in	out	LR	k_a
[34]	NS	SF	58.5	abattoir	24	704	44	94.0	6.8	114	39	66.0	2.5	9.00×10^4	88	2.01	13.4	6.00×10^5	3138	1.28	11.0
[36]				dairy																	
yr. 1 GS [b]	ON	SF	4620		7	152	22	85.7	3.5	-	-	-	-	-	-	-	-	-	-	-	-
yr. 2 GS					7	103	19	81.4	3.1	-	-	-	-	-	-	-	-	-	-	-	-
yr. 3 GS					7	89	20	78.0	2.8	-	-	-	-	-	-	-	-	-	-	-	-
yr. 4 GS					7	99	21	78.9	2.8	-	-	-	-	-	-	-	-	-	-	-	-
[37]	PE	SF	1520	dairy	32	1955	178	90.9	-	828	191	76.9	-	-	-	-	-	1.82×10^4	573	1.50	-
[22] [c]	ON	SF	4620	dairy		-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
[31]	NS	SF	512	tile drain	15	-	-	-	-	-	-	-	-	122	42	0.46	7.7	-	-	-	-
[29]				dairy																	
yr. 1 NGS[d]	ME	SF	690		4	-	-	-	-	1678	51	97.0	38.7	-	-	-	-	-	-	-	-
yr. 2 NGS					4	-	-	-	-	1401	51	96.4	12.1	-	-	-	-	-	-	-	-
[20] GS	NS	SF	1022	dairy	4	736	58	92.1	-	-	-	-	-	-	-	-	-	-	-	-	-
[23]	NS	SF	100	dairy	38	1747	34	98.1	7.0	1450	55	96.2	5.9	-	-	-	-	2.17×10^5	3150	1.84	8.3
[28] GS	ME	SF	690	tile drain	5	-	-	-	-	7700	368	95.2	18.1	-	-	-	-	-	-	-	-
[38]				dairy																	
site 1	ME	SF	360		11	2174	1391	36.0	-	1323	576	56.5	-	-	-	-	-	-	-	-	-
site 2 NGS		SF	270		4	2810	1252	55.4	-	1300	720	44.6	-	-	-	-	-	-	-	-	-
[30]				tile drain																	
yr. 1 GS	QC	SF	1215		7	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
yr. 2 GS					6	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
yr. 3 GS					4	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
yr. 4 GS					6	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
[26]				dairy																	
aerated	NS	SF	100		20	1666	46	97.2	4.0	2537	78	96.9	3.8	4.20×10^5	2797	2.18	5.9	-	-	-	-
non-aerated	NS	SF	100		20	1666	53	96.8	3.7	2537	85	96.7	3.6	4.20×10^5	3869	2.04	5.4	-	-	-	-
[27]				dairy																	
site 1 GS	ON	VSSF	72		6	1022	2.7	99.7	4.1	2595	428	83.5	1.0	6136	4.5	3.13	5.1	-	-	-	-
site 1 NGS					5	1231	3.0	99.8	4.2	1356	4.6	99.7	3.9	1204	6.4	2.27	3.6	-	-	-	-
site 2 GS	ON	VSSF	72		6	906	19	97.9	18.6	633	156	75.4	3.3	2.32×10^4	308.9	1.88	21.3	-	-	-	-
site 2 NGS					5	1128	9.4	99.2	24.1	546	99	81.8	5.1	1287	457.1	0.45	1.0	-	-	-	-
site 3 GS	ON	VSSF	72		6	1164	4.0	99.7	-	951	327	65.6	-	1.53×10^4	46.5	2.52	-	-	-	-	-
stie 3 NGS					5	863	40	95.3	-	317	15	95.3	-	29.1	3.8	0.88	-	-	-	-	-

Table 1. *Cont.*

Study	Prov./ State[a]	CW Type	Area (m^2)	Waste Water Source	Study Length (mo)	BOD_5 ($mg\ L^{-1}$)				TSS ($mg\ L^{-1}$)				*E. coli* (CFU/100 mL)				Fecal Coliforms (CFU/100 mL)			
						in	out	CR %	k_a	in	out	CR %	k_a	In	out	LR	k_a	in	out	LR	k_a
[19]	NS	SF	1022	dairy	24	911	318	65.1	-	410	124	69.7	-	-	-	-	-	-	-	-	-
[35]				winery																	
GS	ON	VSSF	404		36	-	-	-	-	332	2.7	98.0	-	7.66×10^3	24	1.60	-	3.34×10^4	343	1.56	-
NGS					36	-	-	-	-	178	2.9	97.7	-	405	0	-	-	1.87×10^5	117	2.52	-
[39,40]				dairy																	
wetland 1	NS	SF	100		17	1491	18	98.8	-	716	39	94.6	-	-	-	-	-	7438	21	2.55	-
wetland 2	NS	SF	100		17	1491	7.6	99.5	-	716	21	97.1	-	-	-	-	-	7438	24	2.49	-
[41]				dairy																	
yr. 1 GS	ON	SF	4620		7	341	51	85.1	3.4	463	80	82.7	3.2	-	-	-	-	-	-	-	-
yr. 2 GS					7	149	54	64.1	1.9	90	77	14.7	0.4	-	-	-	-	-	-	-	-
[21]				dairy																	
yr. 1	NS	HSSF	200		11	8750	263	97.0	21.5	1063	32	97.0	21.5	2.34×10^6	1.53×10^5	1.18	18.7	-	-	-	-
yr. 2					9	1263	215	83.0	11.3	1922	56	97.1	23.6	6.32×10^4	5.94×10^4	0.03	−1.2	-	-	-	-
[25]				dairy																	
yr. 1 GS [e]	NS	SF	100		6	433	158	63.5	3.6	433	158	63.5	3.6	1.43×10^{12}	2.05×10^{11}	0.84	6.8	-	-	-	-
yr. 1 NGS [e]	NS	SF	100		6	433	57	86.9	-	433	57	86.9	-	-	-	-	-	-	-	-	-
yr. 1 GS [f]	NS	SF	100		6	433	264	38.9	0.5	858	145	83.1	2.8	7.52×10^{11}	1.4×10^{10}	1.73	6.6	-	-	-	-
yr. 1 NGS [f]	NS	SF	100		6	433	162	62.7	0.2	858	134	84.3	1.5	5.43×10^{11}	1.17×10^{11}	0.67	1.0	-	-	-	-
yr. 2 GS [e]	NS	SF	100		6	272	257	5.4	0.8	272	257	5.4	0.8	2.75×10^{11}	4.99×10^9	1.74	7.0	-	-	-	-
yr. 2 NGS [e]	NS	SF	100		6	272	79	71.0	-	272	79	71.0	-	-	-	-	-	-	-	-	-
yr. 2 GS [f]	NS	SF	100		6	272	19	93.0	2.2	877	21	97.6	3.1	1.46×10^{11}	$3.58 x10^8$	2.61	5.0	-	-	-	-
yr. 2 NGS[f]	NS	SF	100		6	272	33	88.0	1.3	877	40	95.4	1.9	5.61×10^{11}	1.10×10^9	2.71	4.0	-	-	-	-
[24]	NS	SF	100	dairy	48	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Mean						1134	157	81.1	6.0	1153	133	82.9	7.7	1.85×10^{11}	1.71×10^{10}	1.63	7.0	7.59×10^5	705	1.93	9.7
Standard Error						267	54.7	3.9	1.4	237	29.3	3.3	2.1	8.32×10^{10}	1.15×10^{10}	0.2	1.5	3.35×10^5	487	0.3	1.4

[a] Nova Scotia (NS), Quebec (QC), Prince Edward Island (PE), Ontario (ON), and Maine (ME); [b] Growing season (May–October); [c] The CW was in its eighth year of operation; [d] Non growing season (November–April); [e] The CW was loaded seasonally; [f] The CW was loaded continuously.

Table 2. Mean influent and effluent concentrations (mg L^{-1}), concentration reductions (CR, %), and areal adjusted rate constants (k_a, m· y^{-1}) for total Kjeldahl nitrogen (TKN), ammonium ($NH^+{}_4$-N), nitrate ($NO^-{}_3$-N), and total phosphorous (TP).

Study	**Prov./State**[a]	**CW Type**	**Area (m^2)**	**Waste Water Source**	**Study Length (mo)**	**TKN**				**$NH_4{}^+$-N**				**$NO_3{}^-$-N**				**TP**			
						in	**Out**	**CR %**	**k_a**	**in**	**out**	**CR %**	**k_a**	**in**	**out**	**CR %**	**k_a**	**in**	**out**	**CR %**	**k_a**
[34]	NS	SF	58.5	abattoir	24	123	21	83.0	4.7	68	6.6	84	5.4	0.1	0.96	-9.4	-	3.1	0.58	81.0	3.7
[36]				dairy																	
yr. 1 GS [b]	ON	SF	4620		7	101	24	76.5	2.7	-	-	-	-	-	-	-	-	17	4.3	74.7	2.5
yr. 2 GS					7	79	27	66.5	2.0	-	-	-	-	-	-	-	-	20	9.1	53.6	1.5
yr. 3 GS					7	70	21	70.4	2.3	-	-	-	-	-	-	-	-	17	8.7	48.8	1.3
yr. 4 GS					7	94	31	67.1	2.1	-	-	-	-	-	-	-	-	18	7.7	56.3	1.6
[37]	PE	SF	1520	dairy	32	402	78	80.6	-	297	46	84.5	-	1.7	1.4	17.6	-	33	8.7	73.6	-
[22][c]	ON	SF	4620	dairy	12	63	31	51.0	-	15	7.2	52.0	-	1.3	1.2	4.7	-	21	13	37.9	-
[31]	NS	SF	512	tile drain	15	-	-	-	-	-	-	-	-	6.7	2.2	67.2	9.2	-	-	-	-
[29]				dairy																	
yr. 1 NGS [d]	ME	SF	690		4	-	-	-	-	-	-	-	-	-	-	-	-	2.6	0.46	82.1	15.2
yr. 2 NGS					4	-	-	-	-	-	-	-	-	-	-	-	-	5.5	0.51	90.8	2.4
[20] GS	NS	SF	1022	dairy	4	301	35	88.5	-	317	18	94.4	-	4.8	0.9	81.3	-	43	6.3	85.5	-
[23]	NS	SF	100	dairy	38	237	19	92.0	4.1	188	14	92.6	4.3	3.7	0.6	83.8	-0.2	37	7.1	80.8	1.6
[28] GS	ME	SF	690	tile drain	5	-	-	-	-	-	-	-	-	-	-	-	-	22	1.7	92.3	13.6
[38]				dairy																	
site 1	ME	SF	360		11	263	238	9.5	-	-	-	-	-	-	-	-	-	81	75	7.4	-
site 2 NGS		SF	270		4	352	369	−4.8	-	180	130	27.8	-	64	96	−50.0	-	-	-	-	-
[30]				tile drain																	
yr. 1 GS	QC	SF	1215		7	-	-	-	-	-	-	-	-	3.1	2.8	9.7	-	91	53	41.9	-
yr. 2 GS					6	-	-	-	-	-	-	-	-	2.9	2.1	27.6	-	45	28	38.2	-
yr. 3 GS					4	-	-	-	-	-	-	-	-	3.9	3.0	23.1	-	92	44	52.4	-
yr. 4 GS					6	-	-	-	-	-	-	-	-	4.4	3.0	31.8	-	82	58	29.2	-
[26]				dairy																	
Aerated	NS	SF	100		20	301	22	92.7	2.6	237	15	93.6	2.8	4.1	1.4	65.9	0.5	50	9.0	81.9	1.4
non-aerated	NS	SF	100		20	301	30	90.0	2.1	237	24	89.7	2.1	4.1	0.7	82.9	1.4	50	8.6	82.7	1.4

Table 2. *Cont.*

Study	Prov./ State[a]	CW Type	Area (m^2)	Waste Water Source	Study Length (mo)	TKN				NH_4^+-N				NO_3^--N				TP			
						in	Out	CR %	k_a	in	out	CR %	k_a	in	out	CR %	k_a	in	out	CR %	k_a
[27]				dairy																	
site 1 GS	ON	VSSF	72		6	69	2.5	96.4	2.1	29	0.7	97.6	2.4	0.5	2.3	-	-	235	17	92.6	1.6
site 1 NGS					5	70	1.8	97.4	2.4	21	0.2	99.1	3.1	0.3	5.9	-	-	127	14	89.0	1.3
site 2 GS	ON	VSSF	72		6	87	34	61.4	0.5	47	22	53.2	−0.7	0.1	5.8	-	-	32	11	66.6	1.4
site 2 NGS					5	112	9.1	91.9	10.1	56	5.5	90.2	9.0	0.2	7.6	-	-	32	12	63.0	0.8
site 3 GS	ON	VSSF	72		6	41	9.4	77.2	-	10	1.2	88.0	-	0.1	2.7	-	-	69	34	50.4	-
stie 3 NGS					5	38	13	65.6	-	4.4	4.2	4.5	-	1.0	0.5	-	-	63	34	46.8	-
[19]	NS	SF	1022	dairy	24	183	53	71.0	-	183	53	71.0	-	3.8	0.9	76.3	-	28	6.0	78.6	-
[35]				winery																	
GS	ON	VSSF	404		36	92.2	0.45	88.7	-	2.18	0.18	72.7	-	0.01	2.03	-	-	5.0	0.17	95.9	-
NGS					36	13.9	0.04	98.8	-	0.91	0.02	98.2	-	0.16	0.83	-	-	2.73	0.23	71.0	-
[39,40]				dairy																	
wetland 1	NS	SF	100		17	173	11	93.5	-	147	8.1	94.5	-	2.4	0.6	76.4	-	44	4.0	91.0	-
wetland 2	NS	SF	100		17	173	3.8	97.8	-	147	1.6	98.9	-	2.5	0.4	85.7	-	44	2.2	95.0	-
[41]				dairy																	
yr. 1 GS	ON	SF	4620		7	145	24	83.2	3.2	107	5.3	95.1	5.4	11	1.0	90.9	4.3	19	13	33.2	0.8
yr. 2 GS					7	-	-	-	-	13	2.1	84.3	3.4	1.0	1.1	-9.7	-0.01	17	11	34.2	0.9
[21]				dairy																	
yr. 1	NS	HSSF	200		11	182	37	80.0	10.9	107	28	74.1	9.1	17	8.7	49.4	4.4	78	10	86.7	13.7
yr. 2					9	58	36	38.0	1.5	62	29	54.0	3.4	3.1	2.3	26.0	0.4	13	10	24.0	0.2
[25]				dairy																	
yr. 1 GS [e]	NS	SF	100		6	327	165	49.5	2.5	23	12	47.8	2.3	-	-	-	-	5.1	2.9	42.0	2.0
yr. 1 NGS [e]	NS	SF	100		6	-	72	-	-	-	3.1	-	-	-	-	-	-	-	-	-	-
yr. 1 GS [f]	NS	SF	100		6	333	75	77.5	2.2	12	3.4	71.3	1.8	-	-	-	-	2.6	1.4	45.4	0.7
yr. 1 NGS [f]	NS	SF	100		6	317	114	64.0	0.2	10	8.5	13.6	−1.1	-	-	-	-	2.1	2.0	3.3	-1.3
yr. 2 GS [e]	NS	SF	100		6	307	69	77.4	3.1	10	1.8	81.4	3.4	-	-	-	-	2.1	0.44	79.0	3.2
yr. 2 NGS [e]	NS	SF	100		6	-	41	-	-	-	0.5	-	-	-	-	-	-	-	-	-	-
yr. 2 GS [f]	NS	SF	100		6	309	13	95.7	2.6	5.3	0.2	95.9	2.7	-	-	-	-	1.1	0.15	86.5	1.7
yr. 2 NGS [f]	NS	SF	100		6	344	30	91.2	1.5	3.7	0.6	84.3	1.1	-	-	-	-	0.88	0.10	89.2	1.3
[24]	NS	SF	100	dairy	48	-	-	-	-	-	-	-	-	-	-	-	-	48	9.7	79.8	1.0
Mean						184	50.3	74.5	3.1	87.6	14.6	75.5	3.3	5.3	5.7	41.6	2.5	39	13.1	64.3	2.9
Standard Error						20.4	12.4	4.2	0.6	18.0	4.5	4.8	0.6	2.3	3.4	9.0	1.2	6.9	2.7	3.9	0.8

[a] Nova Scotia (NS), Quebec (QC), Prince Edward Island (PE), Ontario (ON), and Maine (ME); [b] Growing season (May–October); [c] The CW was in its eighth year of operation; [d] Non growing season (November–April); [e] The CW was loaded seasonally; [f] The CW was loaded continuously.

Table 3. Mean (± standard error) concentration reductions (CR, %), for five-day biochemical oxygen demand (BOD_5), total suspended solids (TSS), total Kjeldahl nitrogen (TKN), ammonium ($NH^+{}_4$-N), nitrate ($NO^-{}_3$-N), and total phosphorous (TP). Mean (± standard error) log reductions (LR) for *E. coli*, and fecal coliforms. The treatment performance is categorized by wetland design, surface flow (SF) or sub-surface flow (SSF) and season, growing season (GS) or non-growing season (NGS).

	SF	SSF	GS	NGS
BOD_5	76.3 ± 4.66	96.5 ± 2.00	76.0 ± 7.04	82.3 ± 6.05
TSS	76.9 ± 5.41	89.1 ± 3.73	69.5 ± 9.54	86.4 ± 4.94
TKN	72.3 ± 5.40	79.5 ± 6.21	76.9 ± 3.54	72.0 ± 13.9
$NH^+{}_4$-N	76.7 ± 5.59	73.2 ± 9.36	80.2 ± 5.19	59.7 ± 16.0
$NO^-{}_3$-N	42.0 ± 9.95	37.7 ± 11.7	36.4 ± 13.9	-
TP	62.8 ± 4.68	68.6 ± 7.38	59.0 ± 4.97	66.9 ± 10.6
E. coli	1.7 ± 0.25	1.5 ± 0.34	2.0 ± 0.25	1.4 ± 0.46
Fecal coliforms	1.9 ± 0.26	2.0 ± 0.48	-	-

2. Constructed Wetland Design

The most common CW designs are surface flow (SF), horizontal subsurface flow (H-SSF) and vertical subsurface flow (V-SSF). However, in the relatively small region of northeastern North America there are no standardized design criteria. Research at the University of Vermont's Constructed Wetland Research Center (CRWC) continues to investigate H-SSF systems, while experiments at the Bio-Environmental Engineering Centre (BEEC) in Bible Hill, Nova Scotia have primarily focused on SF systems. It was suggested [2] that SSF are better suited to Canadian climatic conditions because of their ability to insulate microbial communities from cold winter air temperatures, while Ducks Unlimited endorse SF systems because they are more similar to natural wetlands [42]. The majority of the studies included in this review used SF designs and there were only a few SSF. Therefore, it is not possible to make a conclusion based on the performance data presented in this paper. Many of the CWs considered were designed for the treatment of high solids wastewater from livestock or aquaculture operations. However, different designs can be better suited for the removal of different contaminants found in agricultural wastewater so it may be beneficial to incorporate hybrid designs to take advantage of the strengths of each design.

2.1. Vegetation

Many studies have compared plant species for treatment performance [33,43–46]. Although there is no conclusive species with unanimous acceptance, *Typha* sp. (cattails) tend to be the most commonly used in this region [39,47]. However, it may be best to consider what wetlands plants are found within the area of construction to allow natural succession to determine the species composition after establishment.

2.2. Aeration

The effects of artificial aeration have been examined in a number of experiments, and it generally seems to enhance CW performance [26,44,48–50]. Aeration can increase dissolved oxygen (DO) in a CW system and stimulate organic matter decomposition and plant and microbial respiration, especially during the non-growing season when plant root zones are dormant [26,44,48]. Artificial aeration also induces mechanical mixing and engages stagnant zones to increase active wetland volume, further enhancing performance [49,51].

Nitrification (oxidization of $NH_4{}^+$-N to $NO_2{}^-$-N and then to $NO_3{}^-$-N) is a biologically driven process that is also affected by DO concentrations. Nitrification requires >2 $mg \cdot L^{-1}$ DO but CWs generally have DO concentrations of <1 $mg \cdot L^{-1}$ [26] therefore artificial aeration has the potential to enhance nitrification rates. In a greenhouse mesocosm study, aeration increased nitrification rates by 43% resulting in better $NH_4{}^+$-N treatment [48]. A study [26] compared two similarly loaded parallel

SF CWs, one that was aerated and one was not. The year-round performance of both the systems proved to be similar but the mass reduction of NH_4^+-N in the aerated system was 87%, compared to 78% in the non-aerated system. However, it was concluded that the additional treatment was not significant enough to justify the cost and operation of the aeration system. Another study [44] concluded that aeration increased the removal efficiencies of TSS, TKN, and the chemical oxygen demand (COD) and suggest that CWs should be aerated if the costs of aeration outweigh the costs of reduced treatment efficiencies.

3. Recognized Challenges

3.1. Cold Climate Considerations

Colder temperatures can affect the treatment efficiencies of CWs, but certain design considerations mitigate this issue. The use of SSF *versus* SF helps to limit freezing because the water surface is not exposed to the atmosphere [2]. However, from the data presented in this review both SSF and SF wetlands have also been found effective during winter (Table 3). Two studies [23,39] examined the year-round performance of SF CWs in Atlantic Canada and found that even with the seasonal fluctuations, SF CWs performed well and were suitable water treatment options. Steps can be taken to further improve winter performance of CWs, such as allowing snow and dead vegetation to accumulate on the surface of the wetland to help insulate the system [2,49] and supplemental aeration can prevent freezing [49].

Two loading schedules were compared [25] to determine which would result in better overall treatment: continuous year-round loading *versus* storing the wastewater during the winter and loading the CW only during the summer. It was found that continuous, year-round, loading was the superior option, as it performed better than the seasonally loaded system [25]. The performance of a V-SSF treating winey process water was monitored over six years [35], and it was found that there was no difference in the seasonal performance for the treatment of COD, TSS, TKN, NH_4^+-N, and fecal coliforms. The CW consistently met effluent discharge requirements throughout the six years of monitoring [35].

The data synthesized in this review of 21 studies (Tables 1–3) also suggest that CWs are a suitable option for year-round agriculture wastewater treatment in the cold climate of northeastern North America and this will be addressed in further detail in this paper.

3.2. Phosphorous Management

Soil phosphorus (P) adsorption capacity has been identified as the limiting factor in CW treatment of agricultural wastewater, and it is suggested that research into better substrates for P removal be pursued [52]. Research on CWs with standard substrates (soil and/or gravel) shows that temporary P treatment can be possible, but it can fluctuate significantly depending on the hydrology of the system [24,53]; however, eventually adsorption sites become saturated and treatment performance decreases [54]. A comprehensive assessment of a 4-cell SF system at a 30-head dairy farm considered the P adsorption capacity of the wetland soils [20,53,54]. Initially, the wetland proved capable of P removal (~86% concentration reduction; Table 2), but, over time, the P adsorption capacity decreased, and the wetland's lifespan with respect to P management was estimated to be eight years [20,54].

In eastern Canada and the northeastern USA, the most commonly researched approach to improve CW P management has been post-wetland treatment filters [32,55,56]. Many studies on this topic have taken place in northeastern North America [55,57–60]. Bench-scale experiments have involved columns filled with electric arc furnace (EAF) slag [55], sedimentary *vs.* igneous apatites [57], serpentinite [58], and various combinations of EAF slag, granite and limestone, of three different sizes (fine: 2–5 mm, medium: 5–10 mm, coarse: 10–20 mm) [59]. The latter study retrofitted the outlet of a 28 m^2 H-SSF CW providing tertiary treatment at an aquaculture operation with pilot-scale (300 L) columns containing the best combination (a first column containing medium slag, fine granite, and medium limestone, followed by a second column containing only slag) [47]. From these studies, it was determined that, with appropriate substrate selection, P removal can be possible and EAF emerged as a highly effective and readily available substrate (a by-product from steel manufacturers in Quebec). EAF has a P retention capacity of up to 2.2 $g \cdot kg^{-1}$, which can equate to P reductions ranging from 75% to 100% [56,58,61]. These materials will inevitably reach their P retention limit and need to be exchanged, but this was taken into account by choosing readily available and affordable materials.

4. Treatment Performance

4.1. Areal Rate Constant

Despite its limitations [62], the area-based first-order model (Equation (1)) has become the most widely used representation of CW removal kinetics [63]:

$$k_a = -q\ln\left[\frac{C_{out} - C^*}{C_{in} - C^*}\right] \tag{1}$$

where k_a is the first order area-based plug flow rate constant ($m \cdot y^{-1}$), q is the hydraulic loading rate ($m \cdot y^{-1}$), C_{out} is the outlet concentration ($mg \cdot L^{-1}$ or CFU 100 mL^{-1}), C_{in} is the inlet concentration ($mg \cdot L^{-1}$ or CFU 100 mL^{-1}), and C^* is the background concentration ($mg \cdot L^{-1}$ or CFU 100 mL^{-1}). Of the plug flow assumptions required for the use of this model [64], the most inaccurate is the assumption that inflow and outflow are equal [23]. External hydrologic factors (surface flow into or out of the CW, precipitation, and ET) play important roles in either concentrating [44,65] or diluting [21,23,24,66] wetland effluent, which can skew treatment efficiency calculations. An adjusted first-order rate constant, k_a, has been proposed [23] using the ratio of outflow to inflow to eliminate concentration and dilution effects, according to the following modified equation:

$$k_a = -q\ln\left[\frac{C_{out}\left(\frac{Q_{out}}{Q_{in}}\right) - C^*}{C_{in} - C^*}\right] \tag{2}$$

where $\frac{Q_{out}}{Q_{in}}$ is the ratio of outflow to inflow (dimensionless). When the required data were available, Equation (2) was used to generate rate constants for the purposes of comparison and discussion (Tables 1 and 2). Most studies did not provide background concentration values (C^*), and they were therefore assumed to be zero as the wastewaters considered here were high strength and the C^* values would be minimal compared to C_{in}.

4.2. Wetland Treatment Performance

The performance of the 25 reviewed wetlands is discussed, and, when appropriate, compared to the Livestock Wastewater Treatment Database [1]. They synthesized agricultural treatment wetland performance data throughout the USA. This allows us to compare treatment performance of wetlands in the cold climate of northeastern North America with aggregated data from systems across different climates of the USA. Along with the areal rate constants, the percentages of concentration reductions (CR) or log reductions (LR) are presented (Tables 1 and 2). A summary of the performance data separated by wetland design and season is presented in Table 3. The majority of studies found in the literature only present data in CR, so data were presented similarly here to allow for easy comparisons. CR was calculated using:

$$CR = \frac{C_{in} - C_{out}}{C_{in}} \times 100\% \tag{3}$$

The mean CRs were calculated by taking the mean of the CRs from the available data for each parameter. The standard error of the mean was also calculated by dividing the standard deviation by the square root of the sample size. Standard error is presented with the means in the text and tables.

4.3. BOD_5

The mean (± standard error) BOD_5 influent and effluent concentrations were 1134 ± 267 mg L^{-1} and 157 ± 55 mg L^{-1}, respectively. There was inter-site variation due to the different wastewater characteristics and the uniqueness of each CW. The mean CR of BOD_5 was 81% ± 3.9%, and the rate constant was 6.1 ± 1.4 $m \cdot y^{-1}$. The mean influent and effluent concentrations were higher than those reported by some [1], but the CRs were similar. Overall, CWs are a viable option for the removal BOD_5, and, if designed properly, removal efficiencies of 99% can be possible (Table 1) even with influent concentrations >1000 $mg \cdot L^{-1}$, regardless of season [27].

4.4. Total Suspended Solids

The mean influent and effluent TSS concentrations were 1153 ± 237 $mg \cdot L^{-1}$ and 157 ± 55 $mg \cdot L^{-1}$, respectively. The mean TSS CR was 83% ± 3.3% and the rate constant was 7.7 ± 2.1 $m \cdot y^{-1}$. The data were similar to other studies [1]. Seasonality has no clear effect on TSS removal and year round performance is satisfactory (Table 3). In general, CWs are known to efficiently remove suspended solids [3], and these data reinforce that knowledge.

4.5. Nitrogen

The removal of TKN, NH_4^+-N, and NO_3^--N were assessed when considering CW N management. The mean influent and effluent concentrations for TKN were 184 ± 20 $mg \cdot L^{-1}$ and 50 ± 12 $mg \cdot L^{-1}$, respectively, with a mean CR of 75% ± 4.4% and a k_a of 3.1 ± 0.6 $m \cdot y^{-1}$. For NH_4^+-N, the mean influent and effluent concentrations were 88 ± 18 $mg \cdot L^{-1}$ and 15 ± 5 $mg \cdot L^{-1}$, the average CR was 76% ± 4.8%, and the rate constant 3.3 ± 0.6 $m \cdot y^{-1}$. The TKN and NH_4^+-N removals were higher than expected. N removal by CWs is known to decrease in lower temperatures [67], but the treatment of efficiencies of TKN and NH_4^+-N in the reviewed wetlands were actually higher than the efficiencies reported in warmer climates [1].

The mean influent and effluent NO_3^--N concentrations were 5.3 ± 2.3 $mg \cdot L^{-1}$ and 5.7 ± 3.4 $mg \cdot L^{-1}$. The removal efficiencies of NO_3^--N were usually lower than the other forms of N. NO_3^--N removal occurs through denitrification, which requires anaerobic conditions and a carbon source for the denitrifying bacteria. CWs can be designed to meet those demands and can be quite effective for NO_3^--N removal [68]; however, NO_3^--N was not a top priority for many of the wetlands included in this review, and this is reflected in the treatment data (low influent concentrations and CR) as seen in Table 2.

4.6. Phosphorus

The mean influent and effluent concentrations of TP were 39 ± 7 $mg \cdot L^{-1}$ and 13 ± 3 $mg \cdot L^{-1}$, respectively. The mean CR was 64% ± 3.9%, and the mean k_a value was 2.9 ± 0.8 $m \cdot y^{-1}$. Although some of the systems appeared to be rather successful at removing P (*i.e.*, CRs > 80%; Table 2), the age of the wetland must be taken into account. Phosphorus removal will often be higher in the first few years of operation with decreases over time as the soil adsorption sites become saturated [54]. In six years of monitoring a study, [35] reported that TP removal decreased with time and recommended that additional TP treatment may be necessary. The length of most of the studies included in this review was relatively short (average ~12 months), but it is clear that P treatment is substrate dependant and that, over time, P removal will decrease as a function of loading.

4.7. Pathogens

The capacity of CWs to remove pathogens was assessed by using measurements of *E. coli* or fecal coliforms, which are common indicator organisms used to diagnose fecal contamination. Ten of the 25 wetlands were monitored for *E. coli* and six were monitored for fecal coliforms. The mean influent *E. coli* density was $1.85 \times 10^{11} \pm 8.32 \times 10^{10}$ CFU 100 mL^{-1} and the mean effluent density was

$1.71 \times 10^{10} \pm 1.15 \times 10^{10}$ CFU 100 mL^{-1}. For fecal coliforms the mean influent and effluent densities were $7.59 \times 10^{5} \pm 3.35 \times 10^{5}$ CFU 100 mL^{-1} and 705 ± 487 CFU 100 mL^{-1}. The mean log reductions for *E. coli* and fecal coliforms were 1.63 ± 0.2 and 1.93 ± 0.3, respectively. Mean k_a values were 7.0 ± 1.5 $m \cdot y^{-1}$ for *E. coli* and 9.7 ± 1.4 m y^{-1} for fecal coliforms.

In general, CWs are an effective technology for pathogen removal in cold climates [2,40], and the data support this (Table 1). However, special care needs to be given to make sure the effluent water meets regulatory standards for discharge as human health can be at risk. Although mean treatment results appear to be satisfactory, month-to-month or even day-to-day fluctuations in effluent concentrations could result in health risks, and the resulting discharge limits are therefore very strict.

5. Conclusions

Constructed wetlands are suitable for agricultural wastewater treatment in the cold climate of northeastern North America. We found that CWs are an excellent option for the treatment of BOD_5, TSS, *E. coli*, fecal coliforms, TKN, and NH_4^+-N without significant decreases in performance during the winter months. Some of the other findings are specific to cold climates and some will apply to all CW design:

- Aeration can increase DO and improve treatment performance (specifically NH_4^+-N removal) in certain cases, but the benefits need to outweigh the costs
- Continuous loading throughout the year results in better treatment performance compared to storing the wastewater and loading it only during summer months
- Phosphorous removal remains one of the main weaknesses of CWs, but there is much promising research being conducted on different adsorptive materials that could be used in or in conjunction with CW systems
- It is crucial to properly characterize the wastewater before designing a CW and to consider the maximum loading possible rather than relying on averages
- There is no one CW design (SF, H-SSF, and V-SSF) that is the most effective for agricultural wastewater, but, rather, each design has strengths and weaknesses so hybrid designs may prove to be the most practical
- More research is needed to increase the understanding of CW hydrology and the effects of the various hydrological inputs and outputs on treatment performance and the determination of areal rate constants

It is also worth noting that the availability of performance data from full-scale commercial systems is still limited. Most of the data comes from university run projects, but it would be useful to have access to data from commercial systems. Collaborations between academic researchers and industry members have the potential to greatly increase the knowledge base and to increase the economic return from CWs by improving the technology and finding more applications for it.

Considerable research is being conducted in northeastern North America and CWs are being accepted as a viable solution to the water management issues facing the agricultural sector. Even though there are still research needs, CWs should be considered an option for current agricultural wastewater applications. Many have adopted this view, and, as a result, there are a large amount of full scale, functional CWs found throughout North America, and the world, that are being used to treat various types of wastewater.

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