Pollution 2022, 8(2): 373-396
DOI: 10.22059/POLL.2021.324626.1103

REVIEW PAPER

Constructed Wetlands: A sustainable way of Treating Wastewater in Cold Climate - A review

Adarsh Singh*, **Surjit Singh Katoch, Mukul Bajpai and Akash Rawat**

Department of Civil Engineering, National Institute of Technology Hamirpur, Hamirpur, Himachal Pradesh – 177005, India.

Received: 28.05.2021, Revised: 12.12.2021, Accepted: 21.12.2021

ABSTRACT

The use of constructed wetland (CW) is a natural way of treating wastewater sustainably and economically. However, the implementation of these systems in freezing conditions is still a matter of research and development. The treatment capacity of CWs relies largely on the biological and biochemical processes which further depends on physical conditions such as temperature, solar radiations, etc. Application of wetland systems for treating wastewater faces many challenges in regions with cold climates, resolving which this review has been made. This paper presents a thorough understanding of the components of CWs and their role in contaminant removal. A comprehensive review of the different types of CWs has been done describing the treatment efficiency achieved by its implementation in the cold climate. Furthermore, various technologies which can be clubbed with CWs have also been listed along with the treatment efficiencies obtained. Literature survey indicates that the extent of removing organics (COD and BOD_5) and total phosphorous (TP) are not likely to be affected, but total nitrogen (TN) removal appears to slow down at low temperatures. Despite several advantages of CW technology, further research is required to select suitable macrophytes and optimum design parameters to compensate for frigid conditions.

Keywords: Canna indica, Typha latifolia, macrophytes, total phosphorus, total nitrogen

INTRODUCTION

The exponential increase in global population in the past years has caused the uncontrolled generation of anthropogenic waste causing extreme harm to the environment and human health (Dahiya, 2015; Liyanage & Yamada, 2017). Unplanned industrialization and urbanization have forced the huge population to agglomerate in small spaces increasing the population density of the area. This increased population density has failed the purification capacity of the natural systems, thus increasing the concentration of pollutants in the environment (Bajpai et al., 2019). Types and concentrations of contaminants generated by the usage of resources and released through domestic and industrial means have affected human health and the natural ecosystem adversely. The unavailability of clean drinking water and poor sanitation facilities is a sensitive issue raised on various public podiums throughout the world. An increase in water demand and continuous decline in the quality of surface and groundwater is one of the major concerns globally (Duran-Encalada et al., 2017).

In recent times, the focus of the governments especially in developing countries has been shifted to water reuse and recycling to promote sustainability in the hydrological cycle (Schaum et al., 2015). Given the economic constraints to design, construct and operate

---

* Corresponding Author Email: 19m722@nith.ac.in

conventional wastewater treatment systems, the main stress has been laid on the implementation of innovative methods to treat wastewater at the source of its generation. Artificial or constructed wetland (CW) is an engineered, yet natural way of wastewater treatment (Kadlec and Knight, 1996). A typical CW consists of a pond with substrate media and a special kind of vegetation. Influent flows in the CW and gets treated by physical, chemical, and biological means. CWs improve wastewater quality through various processes such as physical, chemical, and biological (Kadlec and Wallace, 2009; Vymazal, 2010; Garcia et al., 2010). Physical processes include settlement of suspended impurities, filtration, and chemical precipitation takes place when wastewater comes in contact with the substrate media (Tanner et al., 1995). Chemical conversions involve adsorption and ion exchange on the plants and substrate surfaces (Liu et al., 2014). Biological processes such as degradation and conversion of contaminants by microbes and vegetation; nutrients uptake and transformation by microbes and vegetation take place, simultaneously (Vymazal, 2007).

The organics and nutrient removal efficiency of these processes depend on several factors such as vegetation and substrate, pH, dissolved oxygen (DO), temperature, hydraulic loading rates (HLR), hydraulic retention time (HRT), and mode of feeding (Varma et al., 2020; Saeed & Sun, 2012). CW systems are potentially used for treating wastewater as an alternative treatment facility. These have been used globally to treat effluent from different sources such as aquaculture (Gorito et al., 2018; Sindilariu et al., 2007), dairy (Schierano et al., 2018; Smith et al., 2006), tanneries (Ashraf et al., 2018; Calheiros et al., 2012), agricultural runoffs (Mendes et al., 2018; Thorén et al., 2004), municipal sewage (Boonsong et al., 2003; Cameron et al., 2003), etc. Effluent from CW is low in organics and nutrients and possesses the potential to be reclaimed and reused for various uses such as irrigation (Zhang et al., 2019; Ayaz et al., 2015).

Applications of CW systems have shown satisfactory results in the tropical and subtropical parts of the world, but its implementation in the colder region is uncertain. Cold climate is described as the climatic condition where the recorded average temperature in colder months falls below -3°C and in the warmest month, rises to 10°C (Wittgren & Mæhlum, 1997). The cold climate, in general, may refer to polar, tundra, alpine and subarctic climate. However, the studies included in this paper have also crossed the conventional temperature range that cold climate represents, thus exploring various low-temperature ranges that affect the performance of the wetland systems. The treatment capacity of CWs depends primarily on biological phenomena mainly influenced by physical conditions (solar radiation and temperature). Low temperatures inhibit the microbial activity in general, thus affecting its growth and metabolism adversely resulting in poor treatment efficiency (Werker et al., 2002). Also, other processes such as the settlement of suspended impurities, plant uptake, volatilization, filtration, precipitation, and adsorption are influenced by temperature (Stottmeister et al., 2003). The operation of CWs in several countries like Canada, China, Japan, Britain, etc. supports the feasibility of these systems at low temperatures. However several pieces of research are being undertaken worldwide to intensify the factors affecting wetland treatment processes, thus enhancing the treatment efficiency of the wetland system ultimately. In comparison to conventional wastewater treatment methods, these uncertainties make CW applications more dependent on physical conditions. As compared to CW studies in a warm climate, there are relatively fewer researches in cold climatic regions. Figure 1 (a) and Figure 1 (b) shows seasonal variation in the working condition of CWs located in Columbia and despite being covered with snow, the performance of wetland was slightly affected under cold conditions.

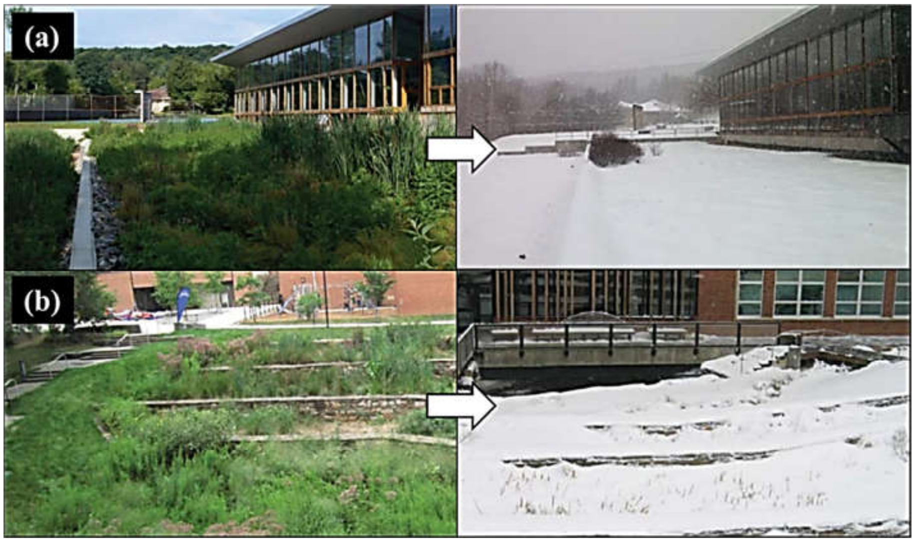

Fig 1: (a) CW at Sidwell Friends Middle School in summer and winter; (b) CW installed at the Omega Center for Sustainable Living in summer and winter (Source: *Biohabitatss 800.220.0919*)

This paper epitomizes the literature available worldwide on the application of CWs in areas with low-temperature conditions. A brief introduction of components and pollutant removal mechanisms have also been included for a better understanding of CWs. Treatment efficiencies of CWs in terms of organics and nutrients have been enlisted in tabular format for easy comparison and comprehension. Moreover, the efficient combinations of CWs with innovative technologies have been discussed along with the overall treatment efficiencies achieved. The present paper also focuses on the economic perspective of CWs in comparison to other treatment technologies. Furthermore, the current review concludes with an explanation of the advantages of CWs over other technologies.

COMPONENTS OF CWs

There are four major components of CWs that play a crucial role in eliminating contaminants from influent wastewater:

Water

CW can be constructed at any place by reshaping the surface to accumulate water and basin sealed up to prevent water seepage. Hydrology is an important design factor in CW technology as it relates all the functions to one another. Any changes in hydrology affect the treatment efficiency of CW significantly (Davis et al., 1995).

Substrate

Substrate media in CW supports vegetation and acts as primary storage for microbial populations thriving in the wetland. Most of the biological and chemical changes occur within the substrate media, making substrate an integral link in the contaminant removal process (Stanković, 2018). Substrate permeability allows the flow of water through the wetland, hence coarser media (sand and gravel) is chosen to avoid clogging hazards.

Macrophytes

Macrophytes play a crucial role in CWs as they supply oxygen to the bottom of wetland through their roots; their stem and root system provide a medium for microbes to attach, thus contributing to the biological treatment of the wastewater (Bani-Melhem et al., 2015). Plants regulate the flow velocities, enabling suspended impurities to settle. They utilize carbon, uptake nutrients and trace metals through their roots, and store them into the plant body. Also, vegetation helps in the exchange of gases between the atmosphere and the substrate (Venkata et al., 2011). Most commonly used plant species include *Canna indica*, *Typha latifolia*, *Phragmites australis*, *Acorus calamus,* etc.

Microorganisms and other life forms

The microbial community of CW includes bacteria, yeast, fungi, protozoa, and algae that help in degrading organic matter and other inorganic substances (Wetzel, 1993). Bacterial species found near water surface is aerobic and degrades organic matter in presence of oxygen. In contrast, the bacterial population near the root level carries out biological treatment anaerobically. Several invertebrates (insects and worms) aid in the process of treatment by breaking down dead and decaying matter, and feeding on organic matter (Venkata et al., 2011).

MECHANISM OF POLLUTANT REMOVAL IN CWs

Organic matter and other impurities present in suspension, settle down to the bottom of CW under gravity. Besides suspended solids, pathogens including *E. coli* and other bacteria get removed through sedimentation. Adsorption and absorption are collectively referred to as sorption, which can be physical or chemical. Phosphorous removal in CWs is primarily due to adsorption (Mann & Bavor, 1993). Furthermore, ammonium ions and certain heavy metals are also eliminated by getting adsorbed to the organic matter present in the wetland system. The extent of ammonium ion adsorption is largely affected by the granular size and chemical composition of substrate media and can be improved by choosing media such as zeolite (Vymazal, 2015). Phosphorous intake by microbes is rapid, though limited due to less storage capacity (Vymazal, 2005).

In the CW system, the classical and newly discovered pathways are followed for the transformation and removal of Nitrogen. The classical routes mainly include biological (nitrification-denitrification processes and plant uptake) and physicochemical routes (ammonia volatilization and adsorption). The first step of nitrogen transformation is ammonification, where organic N gets converted to NH_4^+-N by the enzymatic actions of microorganisms (Vymazal, 2007). After ammonification, the second step is nitrification which involves ammonium ion oxidation to nitrate (NO_3^-) with the formation of nitrite (NO_2^-) as an intermediate product. The first part of the step ($NH_4^+\text{-N} \rightarrow NO_2^-$) is accomplished by chemolithotrophic microorganisms such as *Nitrosomonas* and *Nitrococcus*, aerobically; while the latter step ($NO_2^- \rightarrow NO_3^-$) is led by facultative chemolithotrophic bacteria such as *Nitrospira* and *Nitrobacter*, anaerobically (Reddy et al., 1984). Followed by nitrification, Denitrification is the key and final step for nitrogen removal in CWs (Matheson & Sukias, 2010). During this process, NO_3^- gets converted to molecular nitrogen (N_2), nitrous oxide (N_2O), or nitric oxide (NO) which gets back to the atmosphere. Denitrification occurs in a limited supply of oxygen (DO < 0.3-0.5 mg/L) (Jong et al., 2010). The other environmental parameters that affect the rate of denitrification include pH, redox potential, selection of substrate, and concentration of organic matter.

Microbial metabolism (catabolism and anabolism) causes degradation of soluble organic matter, either aerobically or anaerobically. The final products of anaerobic decomposition include CO_2 and H_2O, and that of aerobic decomposition include CO_2 and CH_4 (Vymazal, 2005). The soluble organic matter gets in contact with bio-layer containing active microbial population which further degrades the organic matter. Nutrient uptake by plants is another crucial mechanism for contaminants removal in CWs. Plants possess the ability to uptake and store inorganic nitrogen, which is later utilized in protein synthesis in plants (Vymazal, 2007). Metals such as Cr, Na, Cu, Se, etc. can also be removed by plants. Metal extracting plants can intake metals like Cd, Zn, Co, Mn, etc. (Guittonny-Philippe et al., 2014).

TYPES OF CONSTRUCTED WETLANDS AND THEIR APPLICATION IN COLD CLIMATE

Based upon hydrological flow patterns CWs have been divided into the following:-

Surface flow constructed wetland (SF-CW)

Surface flow CWs have water surfaces exposed to the atmosphere. It consists of a soil bed grown with emergent and rooted plants. Water in SF CWs flows above 6-18 inches from the substrate surface, depth of flow depends upon the type of plants and design of CW. In SF-CWs, the region close to the water surface is found to be aerobic while at depth anaerobic environment exits. The main mechanisms of removal include in SF-CW include surface adhesion, impurities settlement, and agglomeration. The requirement for a larger land area is the main disadvantage of SF-CW. A schematic representation of SF-CW is shown in figure 2.

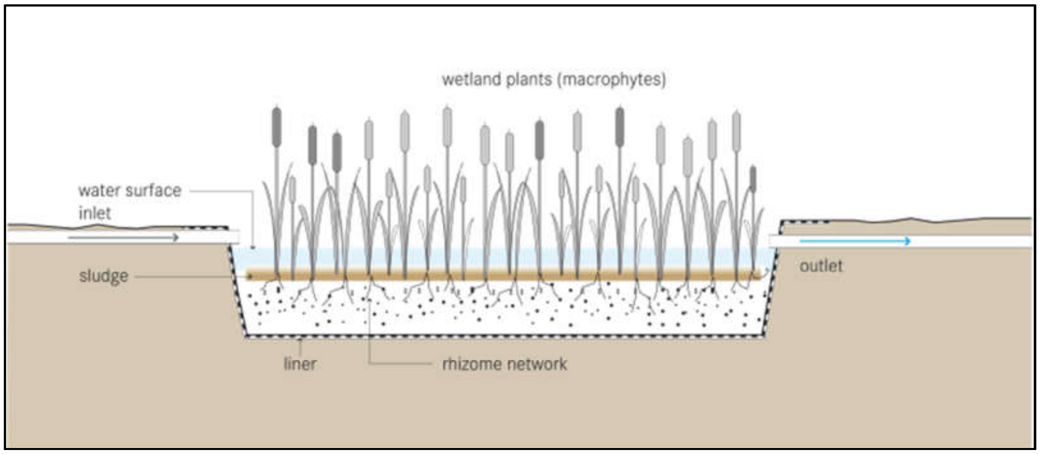

Fig 2: Schematic diagram of Surface flow constructed wetland (SF-CW)
(Source: eCompendium of sanitation systems and technologies)

Application of SF-CWs in cold regions

A lab-scale SF-CW model was developed by (Wu et al., 2018) to investigate the spatial-temporal dynamics of organics and nitrogen removal from secondary effluent under low-temperature conditions (<10 °C). The obtained results indicated that a clear spatial-temporal variation of organics and nitrogen was observed. Organics decay mainly occurred in the surface water and at the interface of water-sediment-plant, while removal of nitrogen was primarily attained in the latter. Low temperature largely affected TN removal in the model. TN removal is hindered due to the restricted supply of carbon for denitrification over the prolonged-time period and could be improved by applying plant carbon sources for denitrification in CWs (Hang et al., 2016). A similar result was drawn by (Kadlec et al., 2012) who successfully monitored a 6.2-hectare marsh implemented in the year 2000 by the Town of Brighton, Ontario. Sufficient treatment was achieved in winters, but the maximum removals were observed in the spring season when the highest growth of vegetation took place. Nutrient reductions were attained, more effectively for phosphorus than for nitrogen.

At Great Village, Nova Scotia, Canada, a SF-CW was designed by (Carreau et al., 2012) to meet the need of having separate treatment systems for discharge from slaughterhouses. A 58.5 m^2 two-celled SF-CW with *Typha latifolia* (Bulrush) was constructed to treat effluent from a small-scale abattoir. The pollutant removal efficiency of SF-CW may be linked with the fact that the actual residence time (111 days) was close to the total residence time. *Escherichia coli* concentration (88 cfu/100 ml) in the CW effluent was found below the permissible limit (200 cfu/100 ml) in most of the samples (Kadlec et al., 2012). Apart from *Typha latifolia*, the contaminant removal efficiency of other plants such as *Potamogeton crispus, Phragmites australis* in SF-CW was tested to treat the polluted river in a cold climate and showed better performance when compared to the unplanted CW system (Fan et al., 2016). An experimental study was performed by Kirby (2002**)** and Cameron et al. (2003) to treat effluent from sewage lagoon for its direct discharge into water bodies. Two additional treatment stages, slag filters (for phosphorous removal) and a filter strip planted with vegetation were provided in the latter. Water samples collected at the inlet and outlet of the CW system were analyzed for BOD_5, TKN, TSS, TP, ortho-phosphate, faecal coliforms, and E. coli. Tests result indicated that CW reduced the concentration of TN, TP, and BOD_5 below the maximum permissible standards allowed for direct discharge into water bodies.

A year-round study was conducted (Smith et al., 2006) to document the treatment processes and removal efficiencies of CWs during winters in Atlantic Canada. Two small-scale CWs of size 100 m^2 operating at different depths were designed and established at the Bio-Environmental Engineering Center of the Nova Scotia Agricultural College to treat agricultural effluent. Percent removal and mass reductions for BOD_5, TSS, TP, and NH_3-N in CWs ranged from 62% - 99%. During high loading periods, TP removal was less effective as compared to other parameters (Chazarenc et al., 2007). A study in the sub-arctic regions, Norway by (Jenssen & Vrale, 2003) showed that biological activity existed in CWs even when the temperature ranged between 0-5°C, and the system was capable of removing organics and nutrients from wastewater. High adsorption of phosphorous could be achieved by the usage of sand having a high content of iron oxide in its composition (Boujelben et al., 2008); also, sand provided a porous medium for adsorption. A properly designed CW with a prolonged retention time can work satisfactorily under cold conditions (Yan & Xu, 2014). SF-CW planted with common reeds has been found effective to improve characteristics of oil-contaminated soil (Ji et al., 2007). The experimental study was carried out for a period of 3 years at Liaohe Oilfield in China. Test results showed that treatment efficiencies ranged between 88 to 92% in the first two years and up to 96% in the third year. The reed bed helped in the recovery of TN and TP from the top 20 cm of soil in the last two years of operation. Throughout the experiment, it was found that reed biomass increased with the increase in oil pollution loading. Also, results suggested that the application of oil-contaminated soil did not have any detrimental effect on the health and growth of reed plants.

The literature surveyed indicates that removal efficiency achieved in SF-CW for TP, TN, NH_4-N, COD, BOD_5, and TSS varied in the range 30-90%, 17-86%, 50-98%, 72-96%, 34-98%, and 45-99% respectively. Treatment efficiencies of SF-CW in cold climatic regions have been listed in table 1.

Table 1: A summary of the treatment efficiency of SF-CW in the cold climate

	Source of effluent	**Flow rate (m^3/day)**	**HRT (day)**	**TP**	**TN**	**NH_4-N**	**COD**	**BOD_5**	**TSS**	**Scale**	**References**
Jinan, China											
Effluent characteristics (mg/l)	Secondary effluent from WWTPs	8.64x10^{-4}	10	0.94	8.32	0.82	14.85	-	-	Lab	Haiming et al., 2018
Removal efficiency (%)				44.38	59.92	90.10	78.93	-	-		
Nova Scotia, Canada											
Effluent characteristics (mg/l)	Slaughterhouse effluent	0.38	108.4	0.58	21	11	-	44	39	Full	Carreau et al., 2012
Removal efficiency (%)				81.29	82.93	83.82	-	93.75	66		
Jinan, Northern China, China											
Effluent characteristics (mg/l)	Synthetic STP effluent (Class IA)	-	-	0.049	6.30	0.31	4.66	-	-	Pilot	Fan et al., 2016
Removal efficiency (%)				92.97	55.62	93.70	92.45	-	-		
Ontario, Canada											
Effluent characteristics (mg/l)	Lagoon WW	3072	9.4	0.255	11.2	9.42	-	3.2	7.2	Full	Kadlec et al., 2012
Removal efficiency (%)				32.5	17.6	16.8	-	40.7	45.45		
Nova Scotia, Canada											
Effluent characteristics (mg/l)	Dairy wastewater (CW-I)	0.3	16	6.9	-	17.8	-	17.4	40.8	Pilot	Smith et al., 2006
Removal efficiency (%)				83.65	-	89.55	-	98.80	94.33		
Nova Scotia, Canada											
Effluent characteristics (mg/l)	Dairy wastewater (CW-II)	0.3	16	4.7	-	3.4	-	11.1	28.2	Pilot	Smith et al., 2006
Removal efficiency (%)				88.86	-	98	-	99.23	96.08		
Tahoe, USA											
Effluent characteristics (mg/l)	Runoff	-	-	0.122	1.02	0.014	-	-	0.01	Full	Heyvaert et al., 2006
Removal efficiency (%)				77.5	48.1	70.2	-	-	91.7		
Ottawa, Canada											
Effluent characteristics (mg/l)	Farm wastewater	-	0.3 months	4.25	43.54	-	-	43.38	44.52	Full	Bosak et al., 2016
Removal efficiency (%)				90	86	-	-	96	99		

	Source of effluent	Flow rate (m^3/day)	HRT (day)	TP	TN	NH_4-N	COD	BOD_5	TSS	Scale	References
Liaoning Province, China	Stabilization pond effluent, wastewater from heavy oil production	18.75	15							Pilot	Ji et al., 2007
Effluent characteristics (mg/l)				-	1.6	-	77	3.9	-		
Removal efficiency (%)				-	86	-	80	88	-		
Ontario, Canada	Municipal lagoon effluent	57.53	15							Pilot	Cameron et al., 2003
Effluent characteristics (mg/l)				0.03	-	0.05	-	2.38	6.18		
Removal efficiency (%)				89.89	-	51.72	-	34	92.52		
Nova Scotia, Canada	Sewage	196.8	42							Full	Kirby, 2002
Effluent characteristics (mg/l)				0.55	4.51	-	-	5	12		
Removal efficiency (%)				83	77	-	-	76	45		
Oslo, Norway	Household sewage	-	-							Pilot	Jenssen et al., 1993
Effluent characteristics (mg/l)				0.2	45	15	60	24	-		
Removal efficiency (%)				98	55	83.52	76	88	-		
Sweden	Agricultural runoff	-	-							Full	Thoren et al., 2004
Effluent characteristics (mg/l)				0.06	4.3	0.4	-	13.4	-		
Removal efficiency (%)				-	32.8	50	-	52.2	-		

Horizontal sub-surface flow constructed wetland (HSSF-CW)

HSSF-CW is commonly known as ‘Reed bed treatment’ in the U.K. and ‘Vegetated submerged beds’ in the U.S.A. consists of a sealed basin with sand or gravel-based substrate. Water in HSSF constructed wetlands flows horizontally through the substrate, below the surface. Due to the water-saturated conditions decomposition processes are limited mainly to anaerobic and anoxic zone. HSSF-CWs are best suited to wastewaters with low suspended impurities and uniform flow i.e. secondary or tertiary treatment of wastewater. Some of the advantages of HSSF CW include tolerance to cold conditions, no pest and odor nuisance, etc. (Ayaz et al., 2015). A schematic representation of HSSF-CW is shown in figure 3.

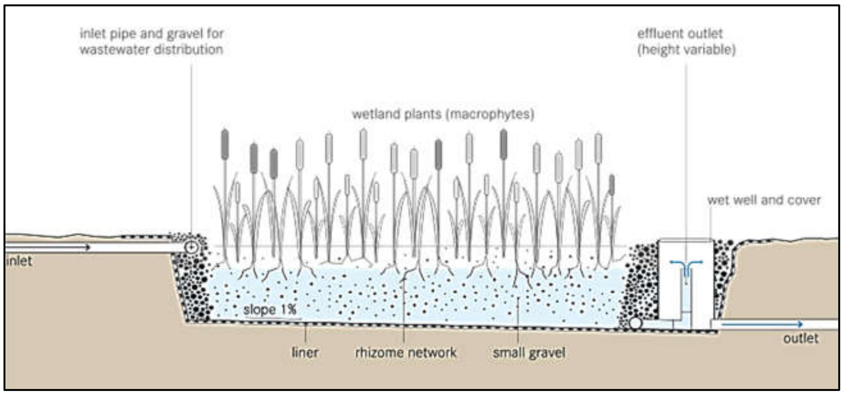

Fig 3: Schematic diagram of Horizontal sub-surface flow constructed wetland (HSSF-CW) (Source: eCompendium of sanitation systems and technologies)

Application of HSSF-CWs in the cold climatic regions

A full-scale trial of a new type of compound double-layer HSSF-CW was conducted by (Pang et al., 2015) operated in the northeast of China for advanced sewage treatment. Results indicated that in the case of ammonia removal, efficiency was found to be low due to limited nitrification at low temperatures. Several measures have been suggested to improve contaminant removal efficiency and operational stability of the wetland system in a cold climate; increasing the depth of the CW, placing layers of insulating mulch layer (Wallace et al., 2001), filling with compound substrate and bio-augmentation. The application of plants *Arundo donax* and *Sarcocornia fruticosa* has been studied to treat saline effluent from a tannery (Calheiros et al., 2012). A *donax* showed higher nutrient uptake compared to *S. fruticosa*. Salt tolerant plant species can be an effective solution to treat effluents induced with salinity (Cheng et al., 2020). The intake capacity of another plant, *Carex aquatilis* was tested for removing nitrogen from municipal wastewater under cold climatic conditions with low light intensity (Yates et al., 2016). The study was conducted at two temperature ranges, 0-5^{o}C and 5-10^{o}C. Test results indicated that *Carex aquatilis* performed well for nutrient removal at both temperatures, compared to a controlled system with no vegetation.

A treatment system consisting of a combination of anaerobic bio-filter followed and a HSSF-CW in Norway was studied for removing organic matter, pathogenic bacteria, nitrogen, and phosphorus from grey-water (Jenssen & Vrale, 2003). The aerobic bio-filter was installed before the CW to remove BOD_5 in a climate where the plants become inactive during winters. Laboratory tests showed that the concentration of pathogenic bacteria in the effluent was within the European permissible limit for swimming water quality. Nutrients concentration in the effluent was also considerably reduced i.e. $N < 5mg/l$; $P < 0.2mg/l$. Another hybrid Norwegian system consisted of three parts; a septic tank, a bio-filter and a HSSF-CW (Paruch et al., 2016). Various preliminary treatments have been suggested to supply air to improve nitrification processes and reduce the concentration of organic matter before wastewater enters the CW system, during winter seasons. The establishment of a pre-treatment chamber and new aeration system improved the treatment efficiencies of the wetland system removing organics and nutrients from leachate generated from Jones County Municipal Landfill near Anamosa, Iowa (Nivala et al., 2007). The HSSF-CW has also proven effective for the reduction of iron; total reactive iron (84%) and total soluble iron (78%) from wastewater (Reuter et al., 1992).

HSSF-CW system is also a prominent solution for treating effluent from a trout farm in cold regions (Sindilariu et al., 2007). The CW treatment efficiency at high HLR was studied by (Sindilariu et al., 2007) in two operational modes i.e. during raceway runoff and cleaning, and was compared with that of sedimentation. Treatment efficiency for TDS removal was found to be highest during the cleaning operation, while TAN treatment efficiency overtopped the removal of other nutrients. Also, the treatment efficiency of HSSF-CW surpassed the treatment effect of the sedimentation basin. To provide the optimum working condition in a cold climate, a novel greenhouse structure has been proposed by researchers. Test results have shown that HSSF CW along with bio-contact oxidation pre-treatment and a greenhouse structure could be operated below 0^{o}C (Gao & Hu, 2012). The use of ornamental plants in these systems can associate economic benefits to the usage of CWs (Gao & Hu, 2012; Sandoval et al., 2019). A HSSF-CW was designed and studied by Rai et al. (2015) to check its potential for removing nutrients and trace elements from urban sewage in Haridwar, India. Three different aquatic plants i.e., *Typha latifolia, Phragmites australis, and Colocasia esculenta* were used. The treatment efficiency for various parameters i.e., conductivity, TDS, BOD, TSS, NO_3-N, NH_4-N, and PO_4-P in the winter and summer season were observed from 55.3–91.61% to 64.8–94.1%, respectively. The planted macrophytes showed a higher bioconcentration factor (BCF) and translocation factor (TF) in summer in comparison to that in the winter season.

The literature surveyed indicates that removal efficiency achieved in HSSF-CW for TP, TN, NH_4-N, COD, BOD_5, and TSS varied in the range 28-98%, 27-75%, 17-85%,5-95%, 87-96%, and 34-82% respectively. Treatment efficiencies of HSSF-CW in cold climatic regions have been listed in table 2.

Table 2: A summary of the treatment efficiency of HSSF-CW in the cold climate

	Source of effluent	**Flow rate (m^3/d)**	**HRT (day)**	**TP**	**TN**	**NH$_4$-N**	**COD**	**BOD$_5$**	**TSS**	**Scale**	**References**
Harbin Taiping, China											
Effluent characteristics (mg/l)	Effluent from biological reactor	36-48	0.8-1.1	0.49	19.7	15.7	46.4	-	-	Full	Pang et al., 2015
Removal efficiency (%)				76.7	42	32	51.5	-	-		
Portugal											
Effluent characteristics (mg/l)	High salinity tannery wastewater	60 mm/d	2	0.25	3.9	1.8	69	11	30	Full	Calheiros et al., 2012
Removal efficiency (%)				82.88	76.07	73.13	64.43	75.55	67.03		
Portugal											
Effluent characteristics (mg/l)	High salinity tannery wastewater	210 mm/d	0.6	0.18	4.3	1.5	92	14	24	Full	Calheiros et al., 2012
Removal efficiency (%)				74.65	58.65	61.54	63.05	79.10	67.12		
Norway											
Effluent characteristics (mg/l)	Domestic sewage (effluent from aerobic bio-filter)	-	6-7	0.07	2.50	2.3	-	6.90	-	Full	Jenssen et al., 2003
Removal efficiency (%)				78.1	50.0	4.2	-	81.9	-		
Bavaria, Germany											
Effluent characteristics (mg/l)	Aquaculture effluent	10.6 m/d	-	36.1 (µg/l)	5.22	18.48 (µg/l)	5.30	1.52	1.76	Full	Sindilariu et al., 2007
Removal efficiency (%)				38.1	-2	86.9	24.3	36.9	34.4		

	Source of effluent	Flow rate (m^3/d)	HRT (day)	TP	TN	NH_4-N	COD	BOD_5	TSS	Scale	References
Shanghai, China											
Effluent characteristics (mg/l)	Dairy wastewater	5.1 L/d	6.5	0.31	14.1	9.1	42.9	-	-	Pilot	Wang et al., 2012
Removal efficiency (%)				91	80	88	87	-	-		
Ontario, Canada											
Effluent characteristics (mg/l)	Municipal WW	-	2-3	-	43.2	35.9	-	-	-	Pilot	Yates et al., 2016
Removal efficiency (%)				-	5	-5	-	-	-		
Oslo, Norway											
Effluent characteristics (mg/l)	Domestic sewage	-	-	0.16	40	39	53	52	41	Full	Paruch et al., 2016
Removal efficiency (%)				98.3	67.5	51.3	91.8	96	68.7		
Heilongjiang, China.											
Effluent characteristics (mg/l)	Domestic sewage	350	1.45	2.09	-	8.58	22.4	-	-	Full	Gao et al., 2012
Removal efficiency (%)				27.3	-	25.4	61	-	-		
Anamosa, Iowa											
Effluent characteristics (mg/l)	Landfill leachate	0.4	-	-	89	14	414	12	-	Pilot	Nivala et al., 2007
Removal efficiency (%)				-	55.9	93	44	88	-		
Beijing, China											
Effluent characteristics (mg/l)	Domestic sewage	270	72	17.6	61.8	63	50	-	-	Pilot	Wang et al., 2008
Removal efficiency (%)				73.6	75.3	87.1	95.1	-	-		
Aosta Valley, Italy											
Effluent characteristics (mg/l)	Dairy wastewater	-	-	6	107	15	-	71	-	Full	Gorra et al.,2014
Removal efficiency (%)				40	27	17	-	92	-		
Haridwar, India											
Effluent characteristics (mg/l)	Sewage	-	1.5	2.85	-	8.7	-	14	48	Full	Rai et al., 2015
Removal efficiency (%)				58.29	-	55.3	-	91.61	82.73		

Vertical sub-surface flow constructed wetland (VSSF-CW)

In VSSF-CW wetlands applied wastewater flows vertically downward through the substrate. A time gap is kept between two hydraulic loadings to allow the movement of air into the pores required for aerobic degradation of organic matter. They have proven effective in removing TSS, OM, and ammonia. Similar to other types, the influent coming to VSSF-CW must be primarily treated to prevent clogging of the substrate media. It requires less area when compared to other types, but high maintenance and operational costs make it less economical (Ayaz et al., 2015). A schematic representation of HSSF-CW is shown in figure 4.

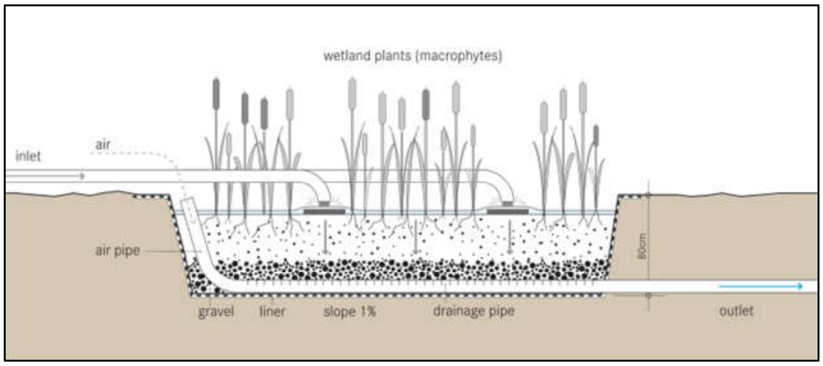

Fig 4: Schematic diagram of Vertical sub-surface flow constructed wetland (VSSF-CW)
(Source: eCompendium of sanitation systems and technologies)

Application of VSSF-CWs in the cold climatic regions

In Beijing, China, a pilot-scale VSSF-CW was built in 2004 near the Longdao River and was found to be viable means for treating polluted water and restoring the Longdao River ecosystem (Chen et al., 2008). The transformed VSSF-CW system was found appropriate as per the local conditions, less expensive to construct, better operation and maintainability than a conventional wastewater method and relatively occupies less land. Another study in the northern part of China indicated that after using the heat preservation measures, VSSF-CW performed well during winters, and the exchange of gas with the air by water happened efficiently, fulfilling oxygen deficiency in the bed, thus improving the pollutant removal ability of the treatment system (Li et al., 2011). The concentration of COD, NH_4^+-N, and TP in the effluent met with the national emission standard.

Literature shows that temperature influences the effectiveness of nitrification and denitrification in wetland systems (Li et al., 2018). A treatment system consisting of VSSF-CW and polishing pond was studied by (Myszograj & Bydałek, 2016) to evaluate the effect of seasonal temperature variation on contaminant removal efficiency of the system. During the monitoring period, the removal efficiency of total nitrogen (TN) was low about 12.7%. During the summer season, the concentration of TN fell by 50% in the treated effluent. During winters, the polishing pond didn't contribute to the treatment efficiency of the whole system. Though studies by other researchers confirm that there is a little seasonal variation on the contaminant removal efficiency of VSSF-CW and the testing result meet with the regulatory limits for discharge to a sub-surface leaching bed (Rozema et al., 2016).

The literature surveyed indicates that removal efficiency achieved in the VSSF-CW for TP, TN, NH_4-N, COD, BOD_5, and TSS varied in the range 40-89%, 30-99%, 40-98%, 82-99%, 86-99%, and 87-99% respectively. Treatment efficiencies of VSSF-CW in cold climatic regions have been listed in table 3.

Table 3: A summary of the treatment efficiency of VSSF-CW in the cold climate

	Source of effluent	**Flow rate (m^3/day)**	**HRT (day)**	**TP**	**TN**	**NH_4-N**	**COD**	**BOD_5**	**TSS**	**Scale**	**References**
Ontario ,Canada	Winery process water and domestic sewage	16.620	-							Full	Rozema et al., 2016
Effluent characteristics (mg/l)				-	0.04	0.02	14.8	0.7	2.9		
Removal efficiency (%)				-	99.71	97.80	99.30	99.95	97.70		

	Source of effluent	Flow rate (m^3/day)	HRT (day)	TP	TN	NH_4-N	COD	BOD_5	TSS	Scale	References
Lubusz Voivodeship, Poland	Domestic sewage	-	0.25							Pilot	Myszograj et al., 2016
Effluent characteristics (mg/l)				-	85	30.9	-	-	-		
Removal efficiency (%)				-	29	70	-	-	-		
Shenyang, China	Domestic sewage	0.154 $m^3/m^2{\cdot}d$	3							Full	Li et al., 2011
Effluent characteristics (mg/l)				-	-	-	-	-	-		
Removal efficiency (%)				89.81	-	97.97	92.36	-	-		
Beijing, China	Domestic sewage	-	-							Full	Chen et al., 2008
Effluent characteristics (mg/l)				0.06	-	4.87	19.25	5.5	6.53		
Removal efficiency (%)				98.4	-	77	81.9	85.9	86.9		
Greece	Municipal wastewater	0.08 $m^3/m^2{\cdot}d$	1.5							Full	Prochaska et al., 2007
Effluent characteristics (mg/l)				-	-	-	-	-	-		
Removal efficiency (%)				38.8	11.9	-	95.9	-	-		
Beijing China	Domestic wastewater	0.12 $m^3/m^2{\cdot}d$	-							Full	Scholz et al., 2004
Effluent characteristics (mg/l)				0.6	-	3.5	-	11.8	3.8		
Removal efficiency (%)				87.8	-	88.4	-	96	97		

Hybrid constructed wetland (HCW)

Hybrid constructed wetlands are an amalgamation of different CW systems (HSSF and VSSF), to obtain high contaminant removal efficiency. Two or three CW with different flow type is arranged either in series or in parallel. These systems are required when removal efficiency is needed in terms of NH_4-N and TN.

Application of HCW in the cold climatic regions

An experimental study conducted in a small mountainous region of Marrakech, Morocco using hybrid CW showed high removal efficiency for organics and nutrients along with total coliforms, fecal coliforms, and fecal streptococci (Elfanssi et al., 2018). Heavy organic loading beyond design limits could deteriorate the treatment efficiency of these systems (Comino et al., 2013). A properly designed hybrid CW system can work efficiently in the extreme temperature range, -22°C - 30°C, even when covered with snow as shown by the test results from a full-scale CW in Hokkaido, Japan (Sharma et al., 2011). Another study in Hokkaido by (Zhang et al., 2017), monitored the treatment performance of the HCW system treating effluent from dairy and piggery. It was found that removal rates obtained in hybrid systems were highest when provided with a higher hydraulic loading rate. The NH_4-N removal efficiency was adversely affected by the COD/TN ratio.

The literature surveyed indicates that removal efficiency achieved in the HCW for TP, TN, NH_4-N, COD, BOD_5, and TSS varied in the range 50-90%, 85-96%, 40-85%, 55-96%, 41-98%, and 46-% respectively. Treatment efficiencies of HCW in cold climatic regions have been listed in table 4.

The conclusion drawn from the collected researches suggests that SF-CWs are not suitable to be used in cold climates because the surface of the water is exposed to the atmosphere which may result in freezing of the influent coming to the wetland system. On the contrary, the water surface in the sub-surface flow CWs remains below the surface of the substrate media and could resist if extreme temperature conditions develop. However, the application of VSSF-CWs is still not recommended because of the problem of bio-clogging. Furthermore, the efficiency of the hybrid system (two or more CW in series or parallel) has been found more than that of the single CW.

Table 4: A summary of the treatment efficiency of HCW in the cold climate

	Layout	**Source of effluent**	**Flow rate (m^3/d)**	**HRT (day)**	**TP**	**TN**	**NH_4-N**	**COD**	**BOD_5**	**TSS**	**Scale**	**References**
Hokkaido, Japan	VF(R) → VF → VF → HF → VF	Dairy effluent (livestock-500)	30.48	-							Full	Zhang et al., 2017
Effluent characteristics (mg/l)					13	34	14	382	106	23		
Removal Efficiency (%)					76	86	40	96	98	84		
Hokkaido, Japan	VF(R) → VF(R) → VF → HF → VF	Piggery wastewater	10.304	-							Full	Zhang et al., 2017
Effluent characteristics (mg/l)					13	397	135	442	50	293		
Removal Efficiency (%)					90	70	85	91	95	94		
Hokkaido, Japan	VF → VF(R) → HF	Dairy effluent (livestock-120)	4.592	-							Full	Zhang et al., 2017
Effluent characteristics (mg/l)					6	21	13	212	92	13		
Removal Efficiency (%)					71	85	76	94	94	97		
Tidili, Morocco	VF → VF → VF → HF → HF	Domestic sewage	0.5-0.75 m^3/m^2.d	-							Full	Elfanssi et al., 2017
Effluent characteristics (mg/l)					3.16	20.19	-	72.93	47.00	46.83		
Removal Efficiency (%)					50	60.60	-	87.24	86.98	90.07		
Italy	VF(R) → VF → HF	Cheese factory wastewater	0.1 m^3/m^2/d	4							Full	Comino et al., 2011
Effluent characteristics (mg/l)					7	4.9	0.5	1129	800	116		
Removal Efficiency (%)					53.4	x	x	54.4	40.7	46.3		
Hokkaido, Japan	VF → VF → HF	Milk parlor wastewater	4.5	-							Full	Sharma et al., 2011
Effluent characteristics (mg/l)					5	32	22	323	138	17		
Removal Efficiency (%)					76	76	64	88	89	98		

COUPLING OTHER TREATMENT PROCESSES WITH CWs

Literature published worldwide summarizes the novel idea of combining constructed wetlands with other treatment processes to improve the overall removal efficiency of these systems in terms of organics (BOD_5, COD), nutrients (TN, TP), and heavy metals. (Kong & Zheng, 2013) integrated a dynamic membrane bio-reactor with VSSF-CW for treating synthetic municipal wastewater. MBR alone has good removal efficiencies for COD and TSS but fails to achieve satisfactory results for nutrient removal; especially when low-cost membranes are used to reduce the capital cost involved (Kimura et al., 2008; Shin et al., 2014). The integrated technology achieved effective TN (80%) and TP (70%) removal. The CWs can also be clubbed with anaerobic processes such as Up-flow anaerobic sludge blanket reactor (UASBR+CW) (El-Khateeb & El-Gohary, 2003) and Anaerobic baffled reactor (ABR+CW)

(Singh et al., 2009; Valipour et al., 2014; Ye et al., 2012). This combination has emerged as a potential solution for wastewater treatment especially for small communities and rural areas. Significant removal of organics and SS in pre-treatment reduces the risk of bio-clogging in CW and enhances its performance. A crucial advantage of this combination lies in the vigorous removal of pathogens and fecal coliforms. In another treatment process called electrolysis, voltages from redox potentials could drive electrochemical reactions, which can cause oxidation of organic matter and ammonium. Electrolysis when integrated with CWs enhances the overall performance of CWs (Grafias et al., 2010; Ju et al., 2014). This technique has gained popularity in recent times, especially for treating wastewater with a low C/N ratio or recalcitrant contaminants. A lab-scale experiment combining electro-flocculation and constructed wetland (EF+CW) has been found efficient in removing phosphate from synthetic wastewater, contributing to the study of reuse potential of CW effluent (Barash et al., 2009). Moving bed bio-film reactor when clubbed with constructed wetlands has been observed to give satisfactory results in term of contaminant removal efficiency (Lai et al., 2020). Treatment efficiencies of various treatment systems, when clubbed with CWs, are given in table 5.

Table 5: Combination of constructed wetlands with other treatment technologies

	Treatment system	Source of effluent	TP	TN	NH_4-N	COD	BOD_5	TSS	Scale	References
Tehran, Iran Removal efficiency (%)	ABR + HSSF-CW	Domestic wastewater	-	79	-	87	93	88	Full	Jamshidi et al., 2014
Nepal Removal efficiency (%)	ABR + HSSF-CW + VSSF-CW	Domestic wastewater	-	26.1	69.5	90.0	90.1	95.9	Full	Singh et al., 2009
China Removal efficiency (%)	MBR + VSSF-CW	Domestic sewage	93.3	85.4	-	90.3	-	-	Full	Kong et al., 2013
China Removal efficiency (%)	ABR + HSSF-CW + SF-CW	Rural sewage	67.25	82.33	-	81.19	-	-	Full	Ye et al., 2012
Cairo, Egypt Removal efficiency (%)	UASBR + HSSF-CW +SF-CW	Municipal wastewater	53.85	47.54	48.39	88.23	93	86.39	Full	El-Khateeb et al., 2003
China Removal efficiency (%)	Electrolysis + SF-CW	Synthetic effluent	-	-	80	85	-	-	Lab	Ju et al., 2014
China Removal efficiency (%)	Electro-flocculation + CW	Synthetic wastewater	90	-	93.2	-	63	67	Lab	Barash et al., 2009
China Removal efficiency (%)	MBBR+ CW	Synthetic wastewater	27.9 – 69.6	46.1 – 84.5	65.0 – 99.3	85.9 – 97.5	-	-	Lab	Lai et al., 2020

ECONOMICS OF CWs

Several researchers have tried to focus on the economic perspective of CW technology. A study conducted by Carlos et al. (2017) compared the performance of WWT systems located on a rural property by Life cycle assessment (LCA). The system studied was UASBR combined with an anaerobic filter, four HSSF-CWs, and two photoreactors. The outcome of the LCA for 10 years indicated that the installation and operational costs for the CWs were the least compared to other technologies. Similar emphasis was drawn from other studies as well (Rahman et al., 2020). Another study conducted by Tsihrintzis et al. (2007) provided a cost comparison (operational & maintenance) for SF-CW and VSSF-CW. The SF-CW system used in the study was designed for a small population of 1200 p.e. and its constructional cost was €305,000, and the capital, operation, and maintenance cost was €22.07/p.e./yr or 0.50/m^3 of influent. On the other hand, the VSSF-CW system was designed for 1000 p.e. construction cost was €410,850, and the capital, operation, and maintenance cost was 36.81/p.e./yr or 0.56/m^3 of influent (Tsihrintzis et al., 2007). The major deciding factor which affects the selection of CWs for wastewater treatment is land availability. Figure 5 shows the area requirement of selected wastewater treatment technologies for secondary treatment for warm to cold climates. When compared to other treatment systems, CWs have a larger land requirement, but less requirement of external energy (pumps) and lower operational & maintenance cost.

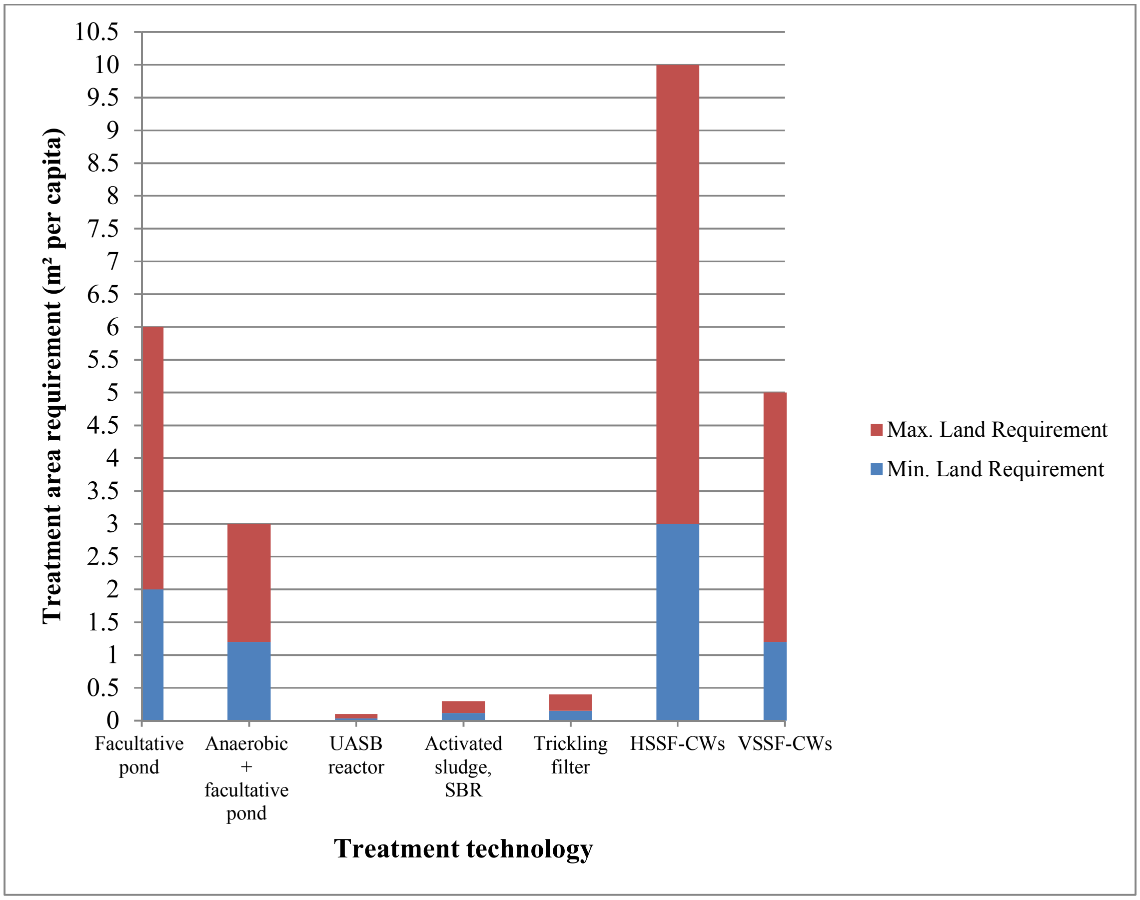

Fig 5: Area requirement of other technologies in comparison to constructed wetlands (CWs). (Source: Hoffmann et al., 2011; Kadlec and Wallace, 2009)

Resende et al. (2019) studied the eco-efficiency of 2 decentralized, small-scale wastewater systems (WWTS) when used in association with CWs. An LCA based on data from two actual pilot structures was carried out. The results implied that the area required for the installation of the system was less when artificial aeration was employed. The life cycle cost per m^3 of treated sewage was 1.8 times smaller for the aerated system when compared to the system without aeration. Thus, aeration is cost-effective for small-scale WWTS coupled to CWs (Resende et al., 2019).

ADVANTAGES OF CW TECHNOLOGY

Water Reclamation or reuse

Treated water received from CWs is low in nutrients and possesses the potential to be reused for non-potable uses such as gardening, landscape irrigation, toilet flushing, etc. as it adheres to the European reuse guidelines (Milani et al., 2020; Nguyen et al., 2020; Nan et al., 2020; Lavrnić & Mancini, 2016).

Use of locally available material and plant species

The substrate material used in CWs such as gravel, river sand, coal cinder, etc., is locally available and has been found fit for use (Wang et al., 2018). The macrophytes suggested by researchers to be used in CWs for nutrient uptake can easily be found in nearby ponds, lakes, and wetlands such as *Phragmites Australis*, *Eichhornia crassipes*, etc. (Shelef et al., 2013).

Economical construction and operation

It is easy to design and construct, requiring less expertise (Ingrao et al., 2020; Rahman et al., 2020). The flow-through treatment stages are entirely gravity driven with no or less pumping action required. Thus, power consumption is less.

Cost benefits

The use of several ornamental plants such as *Canna indica*, *Heliconia*, *Zantedeschia*, etc., must be promoted in CWs as these are aesthetically pleasing and also add income for the locals and municipal agencies (Sandoval et al., 2019).

Environmental friendly

This method of wastewater treatment has a low ecological footprint and causes minimal environmental impact (Gkika et al., 2015). As vegetation planted is herbaceous, hence needs to be harvested once a year. The harvested plants can be used as fodder, compost and can be directly mulched on the surface of CWs to produce thermal insulation in case of extreme winters. Several architects propose CWs in urban localities as a part of landscape beautification and also to improve the wastewater quality in terms of nutrients.

CONCLUSION

- Cold climatic conditions have a significant effect on the treatment capacity of constructed wetlands. CWs in cold climates showed no adverse effect on the removal of TSS, BOD5, COD, but the rate of nitrogen removal (NH_4^+, NO_3^- and NO_2^-) was significantly reduced.
- The use of HSSH-CWs has been found most suited in colder regions, as water surface is not exposed to the atmosphere, thus maintaining an optimum temperature level required for microbial activity.
- Several insulation measures such as vegetation mulching on the wetland surface, bio-augmentation, and constructing glass houses over wetlands have been suggested to

enhance the microbial activity in CWs.

- The problem of bio-clogging was found more frequent in VSSF-CWs, hence unsuitable for effluent with heavy suspended impurities. This indicates a need for the pre-treatment system such as septic tank, Imhoff tank, etc. to make wastewater free from SS before it enters CW.
- Cold climate showed no adverse effect on TP removal as it was mainly eliminated by getting adsorbed on the surface of the substrate. Phosphorous removal in CWs could be enhanced by using iron-enriched substrate media.
- The contaminant removal efficiency of CWs in cold regions was improved by adopting various strategies such as selecting vegetation tolerant to frigid conditions as it plays a crucial role in oxygen supply and maintaining the microbial population in the root zone of plants.
- The use of artificial aerators to increase the level of dissolved oxygen in sub-surface flow CWs and recirculating effluent back into the wetland system helped in the removal of contaminants further by repeated interaction between microbes and contaminants.
- Another way that improved pollutant removal was the use of a hybrid system instead of a single CW. In many cases, to maintain sanitary conditions SF-CW was employed in end as a means to polish effluent before final disposal.

FUTURE SCOPE

- In most of the cases, the concentration of E. coli in the effluent did not meet the regulatory standards implying a need for further disinfection. Chemical disinfection with chlorine compounds leaves behind byproducts again contaminating the treated water. Thus, work could be done to introduce an efficient, yet economical way of disinfecting effluent from CW.
- Salinity in the effluent is detrimental to biological components of the wetland system, especially vegetation. Work needs to be done to incorporate salt-tolerant macrophytes such as mangrove species in the CWs because of their high tolerance to a saline environment.
- Vegetation harvested from CWs is heavily doped with nutrients and metals, if disposed of directly on land may cause toxicity in the soil. Currently, no effective measures are known for the proper management of harvested vegetation. Thus, work needs to be done suggesting measures for proper handling and disposal of harvested macrophytes.
- Bio-augmentation in CWs could be done to aid microbial growth and enhance their metabolism in a cold climate, though sufficient knowledge is not available in this regard.

ACKNOWLEDGEMENT

The author would like to thank the Department of Civil Engineering of National Institute of Technology Hamirpur, Himachal Pradesh, India, and my colleagues for providing valuable support to carry out this research.

GRANT SUPPORT DETAILS

The present research did not receive any financial support.

CONFLICT OF INTEREST

The authors declare that there is not any conflict of interests regarding the publication of this manuscript. In addition, the ethical issues, including plagiarism, informed consent, misconduct, data fabrication and/ or falsification, double publication and/or submission, and redundancy has been completely observed by the authors.

LIFE SCIENCE REPORTING

No life science threat was practiced in this research.

REFERENCES

Ashraf, S., Afzal, M., Naveed, M., Shahid, M. and Ahmad Zahir, Z. (2018). Endophytic bacteria enhance remediation of tannery effluent in constructed wetlands vegetated with Leptochloa fusca. *International Journal of Phytoremediation*, *20*(2), 121–128.

Ayaz, S. Ç., Aktaş, Ö., Akça, L. and Fındık, N. (2015). Effluent quality and reuse potential of domestic wastewater treated in a pilot-scale hybrid constructed wetland system. *Journal of Environmental Management*, *156*, 115–120.

Bajpai, M., Katoch, S. S. and Chaturvedi, N. K. (2019). Comparative study on decentralized treatment technologies for sewage and graywater reuse – a review. *Water Science and Technology*, *80*(11), 2091–2106.

Bani-Melhem, K., Al-Qodah, Z., Al-Shannag, M., Qasaimeh, A., Rasool Qtaishat, M. and Alkasrawi, M. (2015). On the performance of real grey water treatment using a submerged membrane bioreactor system. *Journal of Membrane Science*, *476*, 40–49.

Barash, A., Ozer, K., Adin, A., Sciences, W., Hebrew, T., Milstein, D. and Gasith, A. (2009). *Electroflocculation – Constructed Wetland Hybrid for Improved Phosphate Removal In Effluent Reuse Keywords*.

Boonsong, K., Piyatiratitivorakul, S. and Patanaponpaiboon, P. (2003). Potential use of mangrove plantation as constructed wetland for municipal wastewater treatment. *Water Science and Technology*, *48*(5), 257–266.

Bosak, V., VanderZaag, A., Crolla, A., Kinsley, C. and Gordon, R. (2016). Performance of a Constructed Wetland and Pretreatment System Receiving Potato Farm Wash Water. *Water*, *8*(5), 183.

Boujelben, N., Bouzid, J., Elouear, Z., Feki, M., Jamoussi, F. and Montiel, A. (2008). Phosphorus removal from aqueous solution using iron coated natural and engineered sorbents. *Journal of Hazardous Materials*, *151*(1), 103–110.

Calheiros, C. S. C., Quitério, P. V. B., Silva, G., Crispim, L. F. C., Brix, H., Moura, S. C. and Castro, P. M. L. (2012). Use of constructed wetland systems with Arundo and Sarcocornia for polishing high salinity tannery wastewater. *Journal of Environmental Management*, *95*(1), 66–71.

Cameron, K., Madramootoo, C., Crolla, A. and Kinsley, C. (2003). Pollutant removal from municipal sewage lagoon effluents with a free-surface wetland. *Water Research*, *37*(12), 2803–2812.

Carreau et al. (2012). *Evaluation of a surface flow constructed wetland treating abattoir wastewater*. *28*(5), 757–766.

Chazarenc, F., Maltais-Landry, G., Troesch, S., Comeau, Y. and Brisson, J. (2007). Effect of loading rate on performance of constructed wetlands treating an anaerobic supernatant. *Water Science and Technology : A Journal of the International Association on Water Pollution Research*, *56*(3), 23–29.

Chen, Z. M., Chen, B., Zhou, J. B., Li, Z., Zhou, Y., Xi, X. R., Lin, C. and Chen, G. Q. (2008). A vertical subsurface-flow constructed wetland in Beijing. *Communications in Nonlinear Science and Numerical Simulation*, *13*(9), 1986–1997.

Cheng, R., Zhu, H., Cheng, X., Shutes, B. and Yan, B. (2020). Saline and alkaline tolerance of wetland plants-what are the most representative evaluation indicators? *Sustainability (Switzerland)*, *12*(5), 1–18.

Comino, E., Riggio, V. A. and Rosso, M. (2013). Constructed wetland treatment of agricultural effluent from an anaerobic digester. *Ecological Engineering*, *54*, 165–172.

Comino, E., Riggio, V. and Rosso, M. (2011). Mountain cheese factory wastewater treatment with the use of a hybrid constructed wetland. *Ecological Engineering*, *37*(11), 1673–1680.

Dahiya, R. (2015). Projections for the Population Growth and Its Impact on Solid Waste Generation of a Medium Sized North. *International Journal of Technical Research and Applications*, *3*(6), 57–61.

Davor Stanković. (2018). Constructed wetlands for wastewater treatment. *Encyclopedia of Ecology*, *69*, 14–21.

Duran-Encalada, J. A., Paucar-Caceres, A., Bandala, E. R. and Wright, G. H. (2017). The impact of global climate change on water quantity and quality: A system dynamics approach to the US–Mexican transborder region. *European Journal of Operational Research*, *256*(2), 567–581.

El-Khateeb, M. A. and El-Gohary, F. A. (2003). Combining UASB technology and constructed wetland for domestic wastewater reclamation and reuse. *Water Supply*, *3*(4), 201–208.

Elfanssi, S., Ouazzani, N., Latrach, L., Hejjaj, A. and Mandi, L. (2018). Phytoremediation of domestic wastewater using a hybrid constructed wetland in mountainous rural area. *International Journal of Phytoremediation*, *20*(1), 75–87.

Fan, J., Zhang, J., Ngo, H. H., Guo, W. and Yin, X. (2016). Improving low-temperature performance of surface flow constructed wetlands using Potamogeton crispus L. plant. *Bioresource Technology*, *218*, 1257–1260.

Gao, D. and Hu, Q. (2012). Bio-contact oxidation and greenhouse-structured wetland system for rural sewage recycling in cold regions: A full-scale study. *Ecological Engineering*, *49*, 249–253.

García, J., Rousseau, D. P. L., Morató, J., Lesage, E., Matamoros, V. and Bayona, J. M. (2010). Contaminant Removal Processes in Subsurface-Flow Constructed Wetlands: A Review. *Critical Reviews in Environmental Science and Technology*, *40*(7), 561–661.

Gkika, D., Gikas, G. D. and Tsihrintzis, V. A. (2015). Environmental footprint of constructed wetlands treating wastewater. *Journal of Environmental Science and Health. Part A, Toxic/Hazardous Substances & Environmental Engineering*, *50*(6), 631–638.

Gorito, A. M., Ribeiro, A. R., Gomes, C. R., Almeida, C. M. R. and Silva, A. M. T. (2018). Constructed wetland microcosms for the removal of organic micropollutants from freshwater aquaculture effluents. *Science of the Total Environment*, *644*, 1171–1180.

Gorra, R., Freppaz, M., Zanini, E. and Scalenghe, R. (2014). Mountain dairy wastewater treatment with the use of a “irregularly shaped” constructed wetland (Aosta Valley, Italy). *Ecological Engineering*, *73*, 176–183.

Grafias, P., Xekoukoulotakis, N. P., Mantzavinos, D. and Diamadopoulos, E. (2010). Pilot treatment of olive pomace leachate by vertical-flow constructed wetland and electrochemical oxidation: An efficient hybrid process. *Water Research*, *44*(9), 2773–2780.

Guittonny-Philippe, A., Masotti, V., Höhener, P., Boudenne, J. L., Viglione, J. and Laffont-Schwob, I. (2014). Constructed wetlands to reduce metal pollution from industrial catchments in aquatic Mediterranean ecosystems: A review to overcome obstacles and suggest potential solutions. *Environment International*, *64*, 1–16.

Hang, Q., Wang, H., Chu, Z., Ye, B., Li, C. and Hou, Z. (2016). Application of plant carbon source for denitrification by constructed wetland and bioreactor: review of recent development. *Environmental Science and Pollution Research*, *23*(9), 8260–8274.

Heyvaert, A. C., Reuter, J. E. and Goldman, C. R. (2006). Subalpine, cold climate, stormwater treatment with a constructed surface flow wetland. *Journal of the American Water Resources Association*, *42*(1), 45–54.

Hoffmann H., Platzer C., Winker M. and Von Muench E. (2011) Technology review of constructed wetlands: Subsurface flow constructed weltands for greywater and domestic wastewater treatment. http://www.susana.org/en/resources/library/details/930, last accessed 25 May 2017. Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ): Eschborn, Germany.

Ingrao, C., Failla, S. and Arcidiacono, C. (2020). A comprehensive review of environmental and operational issues of constructed wetland systems. *Current Opinion in Environmental Science & Health*, *13*, 35-45.

Jamshidi, S. and Khalesidoost, M. (2014). Biogas production yield of anaerobic baffled reactor in low pH and HRT. *Journal of Middle East Applied Science and Technology*, *15*(15), 765–770.

Jenssen, P. D., Mæhlum, T. and Krogstad, T. (1993). Potential Use of Constructed Wetlands for Wastewater Treatment in Northern Environments. *Water Science and Technology*, *28*(10), 149–157.

Jenssen P, D. and Vrale L. (2003). Greywater Treatment in combined Biofilter/Constructed Wetlands in Cold Climate. *Ecosan – Closing the Loop. Proc. 2nd Int. Symp. Ecological Sanitation, Lübeck*, 875–881.

Ji, G. D., Sun, T. H. and Ni, J. R. (2007). Surface flow constructed wetland for heavy oil-produced water treatment. *Bioresource Technology*, *98*(2), 436–441.

Jong, J., Lee, J., Kim, J., Hyun, K., Hwang, T., Park, J. and Choung, Y. (2010). The study of pathogenic microbial communities in graywater using membrane bioreactor. *Desalination*, *250*(2), 568–572.

Ju, X., Wu, S., Huang, X., Zhang, Y. and Dong, R. (2014). How the novel integration of electrolysis in tidal flow constructed wetlands intensifies nutrient removal and odor control. *Bioresource Technology*, *169*, 605–613.

Kadlec R.H. and Wallace S.D. (2009) Treatment Wetlands, Second Edition. Boca Raton, Florida: CRC Press.

Kadlec, R. H., Pries, J. and Lee, K. (2012). The Brighton treatment wetlands. *Ecological Engineering*, *47*, 56–70.

Kimura, K., Nishisako, R., Miyoshi, T., Shimada, R. and Watanabe, Y. (2008). Baffled membrane bioreactor (BMBR) for efficient nutrient removal from municipal wastewater. *Water Research*, *42*(3), 625–632.

Kirby, A. (2002). Wastewater Treatment Using Constructed Wetlands. *Canadian Water Resources Journal*, *27*(3), 263–272.

Kong, L., He, F., Xia, S., Xu, D., Zhang, Y., Xiao, E. R. and Wu, Z. B. (2013). A combination process of DMBR-IVCW for domestic sewage treatment. *Fresenius Environ. Bull*, *22*(3), 665-674.

Lai, C., Sun, Y., Guo, Y., Cai, Q. and Yang, P. (2020). A novel integrated bio-reactor of moving bed and constructed wetland (MBCW) for domestic wastewater treatment and its microbial community diversity. *Environmental Technology*, *0*(0), 1–16.

Lavrnić, S. and Mancini, M. L. (2016). Can constructed wetlands treat wastewater for reuse in agriculture? Review of guidelines and examples in South Europe. *Water Science and Technology*, *73*(11), 2616–2626.

Li, J., Fan, J., Zhang, J., Hu, Z. and Liang, S. (2018). Preparation and evaluation of wetland plant-based biochar for nitrogen removal enhancement in surface flow constructed wetlands. *Environmental Science and Pollution Research*, *25*(14), 13929–13937.

Li, Y., Zhang, Y. and Zhang, X. (2011). Heat preservation of subsurface flow constructed wetland in cold area in winter and its operation effect. *Procedia Environmental Sciences*, *10*(PART C), 2182–2188.

Liyanage, C. P. and Yamada, K. (2017). Impact of population growth on the water quality of natural water bodies. *Sustainability (Switzerland)*, *9*(8).

Lutterbeck, Carlos A., Kist, Lourdes T., Lopez, Diosnel R., Zerwes, Filipe V. and Machado, Ênio L. (2017). *Life cycle assessment of integrated wastewater treatment systems with constructed wetlands in rural areas. Journal of Cleaner Production, 148(), 527–536.*

Varma, M., Gupta, A. K., Ghosal, P. S. and Majumder, A. (2021). A review on performance of constructed wetlands in tropical and cold climate: Insights of mechanism, role of influencing factors, and system modification in low temperature. *Science of The Total Environment*, *755*, 142540.

Mann, R. A. and Bavor, H. J. (1993). Phosphorus removal in constructed wetlands using gravel and industrial waste substrata. *Water Science and Technology*, *27*(1), 107–113.

Matheson, F. E. and Sukias, J. P. (2010). Nitrate removal processes in a constructed wetland treating drainage from dairy pasture. *Ecological Engineering*, *36*(10), 1260–1265.

Mendes, L. R. D., Tonderski, K. and Kjaergaard, C. (2018). Phosphorus accumulation and stability in sediments of surface-flow constructed wetlands. *Geoderma*, *331*(June), 109–120.

Milani, M., Consoli, S., Marzo, A., Pino, A., Randazzo, C., Barbagallo, S. and Cirelli, G. L. (2020). Treatment of winery wastewater with a multistage constructed wetland system for irrigation reuse. *Water*, *12*(5), 1260.

Myszograj, S. and Bydałek, F. (2016). Temperature Impact of Nitrogen Transformation in Technological System: Vertical Flow Constructed Wetland and Polishing Pond. *Civil And Environmental Engineering Reports*, *23*(4), 125–136.

Nan, X., Lavrnić, S. and Toscano, A. (2020). Potential of constructed wetland treatment systems for agricultural wastewater reuse under the EU framework. *Journal of Environmental Management*, *275*, 111219.

Nivala, J., Hoos, M. B., Cross, C., Wallace, S. and Parkin, G. (2007). Treatment of landfill leachate using an aerated, horizontal subsurface-flow constructed wetland. *Science of The Total Environment*, *380*(1–3), 19–27.

Nguyen, X. C., Tran, T. P., Hoang, V. H., Nguyen, T. P., Chang, S. W., Nguyen, D. D. and Bach, Q. V. (2020). Combined biochar vertical flow and free-water surface constructed wetland system for dormitory sewage treatment and reuse. *Science of The Total Environment*, *713*, 136404.

Pang, C., Li, A., Qiu, S., Wang, L., Yang, J., Ma, F. and Ren, N. (2015). *A novel subsurface flow constructed wetland system used in anvanced wastewater treatment for nutrient removal in a cold area*. *47*(D), 173–178.

Paruch, A. M., Mæhlum, T., Haarstad, K., Blankenberg, A.G. B. and Hensel, G. (2016). Natural and Constructed Wetlands. *Natural and Constructed Wetlands*, (1431), 41–55.

Prochaska, C. A., Zouboulis, A. I. and Eskridge, K. M. (2007). Performance of pilot-scale vertical-flow constructed wetlands, as affected by season, substrate, hydraulic load and frequency of application of simulated urban sewage. *Ecological Engineering*, *31*(1), 57–66.

Rahman, M. E., Bin Halmi, M. I. E., Bin Abd Samad, M. Y., Uddin, M. K., Mahmud, K., Abd Shukor, M. Y., Abdullah, S.R.S. and Shamsuzzaman, S. M. (2020). Design, Operation and Optimization of Constructed Wetland for Removal of Pollutant. *International Journal of Environmental Research and Public Health*, *17*(22), 8339.

Rai, U. N., Upadhyay, A. K., Singh, N. K., Dwivedi, S. and Tripathi, R. D. (2015). Seasonal applicability of horizontal sub-surface fl ow constructed wetland for trace elements and nutrient removal from urban wastes to conserve Ganga River water quality at Haridwar , India. *Ecological Engineering*, *81*, 115–122.

Reddy, K. R., Patrick, W. H. and Broadbent, F. E. (1984). Nitrogen transformations and loss in flooded soils and sediments. *C R C Critical Reviews in Environmental Control*, *13*(4), 273–309.

Resende, J. D., Nolasco, M. A. and Pacca, S. A. (2019). Life cycle assessment and costing of wastewater treatment systems coupled to constructed wetlands. *Resources, Conservation and Recycling*, *148*, 170-177.

Reuter, J. E., Djohan, T. and Goldman, C. R. (1992). The use of wetlands for nutrient removal from surface runoff in a cold climate region of california-results from a newly constructed wetland at lake tahoe. *Journal of Environmental Management*, *36*(1), 35–53.

Rozema, E. R., Rozema, L. R. and Zheng, Y. (2016). A vertical flow constructed wetland for the treatment of winery process water and domestic sewage in Ontario, Canada: Six years of performance data. *Ecological Engineering*, *86*, 262–268.

Saeed, T. and Sun, G. (2012). A review on nitrogen and organics removal mechanisms in subsurface flow constructed wetlands: Dependency on environmental parameters, operating conditions and supporting media. *Journal of Environmental Management*, *112*, 429–448.

Sandoval, L., Zamora-castro, S. A., Á, M. V. and Mar, L. (2019). *applied sciences Role of Wetland Plants and Use of Ornamental Flowering Plants in Constructed Wetlands for Wastewater Treatment : A Review*. 1–17.

Schaum, C., Lensch, D. and Cornel, P. (2015). Water reuse and reclamation: A contribution to energy efficiency in the water cycle. *Journal of Water Reuse and Desalination*, *5*(2), 83–94.

Schierano, M. C., Panigatti, M. C. and Maine, M. A. (2018). Horizontal subsurface flow constructed wetlands for tertiary treatment of dairy wastewater. *International Journal of Phytoremediation*, *20*(9), 895–900.

Scholz, M. (2004). Treatment of gully pot effluent containing nickel and copper with constructed wetlands in a cold climate. *Journal of Chemical Technology and Biotechnology*, *79*(2), 153–162.

Sharma, P. K., Inoue, T., Kato, K., Ietsugu, H., Tomita, K. and Nagasawa, T. (2011). Potential of hybrid constructed wetland system in treating milking parlor wastewater under cold climatic conditions in northern Hokkaido, Japan. *Water Practice and Technology*, *6*(3).

Shelef, O., Gross, A. and Rachmilevitch, S. (2013). Role of plants in a constructed Wetland: Current and new perspectives. *Water (Switzerland)*, *5*(2), 405–419.

Shin, C., McCarty, P. L., Kim, J. and Bae, J. (2014). Pilot-scale temperate-climate treatment of domestic wastewater with a staged anaerobic fluidized membrane bioreactor (SAF-MBR). *Bioresource Technology*, *159*, 95–103.

Sindilariu, P., Schulz, C. and Reiter, R. (2007). Treatment of flow-through trout aquaculture effluents in a constructed wetland. *Aquaculture*, *270*(1–4), 92–104.

Singh, S., Haberl, R., Moog, O., Shrestha, R. R., Shrestha, P. and Shrestha, R. (2009). Performance of an anaerobic baffled reactor and hybrid constructed wetland treating high-strength wastewater in Nepal—A model for DEWATS. *Ecological Engineering*, *35*(5), 654–660.

Smith, E., Gordon, R., Madani, A. and Stratton, G. (2006). Year-round treatment of dairy wastewater by constructed wetlands in Atlantic Canada. *Wetlands*, *26*(2), 349–357.

Stottmeister, U., Wießner, A., Kuschk, P., Kappelmeyer, U., Kästner, M., Bederski, O., Muller, R.A. and Moormann, H. (2003). Effects of plants and microorganisms in constructed wetlands for wastewater treatment. *Biotechnology Advances*, *22*(1–2), 93–117.

Tanner, C. C., Clayton, J. S. and Upsdell, M. P. (1995). Effect of loading rate and planting on treatment of dairy farm wastewaters in constructed wetlands-I. Removal of oxygen demand, suspended solids and faecal coliforms. *Water Research*, *29*(1), 17–26.

Thorén, A. K., Legrand, C. and Tonderski, K. S. (2004). Temporal export of nitrogen from a constructed wetland: Influence of hydrology and senescing submerged plants. *Ecological Engineering*, *23*(4–5), 233–249.

Tsihrintzis, V. A., Akratos, C. S., Gikas, G. D., Karamouzis, D. and Angelakis, A. N. (2007). Performance and Cost Comparison of a FWS and a VSF Constructed Wetland System. Environmental Technology, 28(6), 621–628.

Valipour, A., Taghvaei, S. M., Raman, V. K., Gholikandi, G. B., Jamshidi, S. and Hamnabard, N. (2014). An approach on attached growth process for domestic wastewater treatment. *Environmental Engineering and Management Journal*, *13*(1), 145–152.

Venkata Mohan, S., Mohanakrishna, G. and Chiranjeevi, P. (2011). Sustainable power generation from floating macrophytes based ecological microenvironment through embedded fuel cells along with simultaneous wastewater treatment. *Bioresource Technology*, *102*(14), 7036–7042.

Vymazal, J. (2005). Constructed wetlands for wastewater treatment. *Ecological Engineering*, *25*(5), 475–477.

Vymazal, J. (2007). Removal of nutrients in various types of constructed wetlands. *Science of the Total Environment*, *380*(1–3), 48–65.

Vymazal, J. (2010). Constructed wetlands for wastewater treatment. *Water (Switzerland)*, *2*(3), 530–549.

Vymazal, J. (2015). The Role of Natural and Constructed Wetlands in Nutrient Cycling and Retention on the Landscape. In J. Vymazal (Ed.), *The Role of Natural and Constructed Wetlands in Nutrient Cycling and Retention on the Landscape*.

Wallace, S., Parkin, G. and Cross, C. (2001). Cold climate wetlands: design and performance. *Water Science and Technology*, *44*(11–12), 259–265.

Wang, F., Liu, Y., Ma, Y., Wu, X. and Yang, H. (2012). Characterization of nitrification and microbial community in a shallow moss constructed wetland at cold temperatures. *Ecological*

Engineering, *42*, 124–129.

Wang, H. X., Xu, J. L., Sheng, L. X. and Liu, X. J. (2018). A Review of Research on Substrate Materials for Constructed Wetlands. *Materials Science Forum*, *913*, 917–929.

Werker, A. G., Dougherty, J. M., McHenry, J. L. and Van Loon, W. A. (2002). Treatment variability for wetland wastewater treatment design in cold climates. *Ecological Engineering*, *19*(1), 1–11.

Wittgren, H. B. and Mæhlum, T. (1997). Wastewater treatment wetlands in cold climates. *Water Science and Technology*, *35*(5), 45–53.

Wu, H., Ma, W., Kong, Q. and Liu, H. (2018). Spatial-temporal dynamics of organics and nitrogen removal in surface flow constructed wetlands for secondary effluent treatment under cold temperature. *Chemical Engineering Journal*, *350*(June), 445–452.

Yan, Y. and Xu, J. (2014). Improving winter performance of constructed wetlands for wastewater treatment in northern china: A Review. *Wetlands*, *34*(2), 243–253.

Yates, C. N., Varickanickal, J., Cousins, S. and Wootton, B. (2016). Testing the ability to enhance nitrogen removal at cold temperatures with C. aquatilis in a horizontal subsurface flow wetland system. *Ecological Engineering*, *94*, 344–351.

Ye, C., Li, L., Zhang, J. and Yang, Y. (2012). Study on ABR Stage-Constructed Wetland Integrated System in Treatment of Rural Sewage. *Procedia Environmental Sciences*, *12*(Icese 2011), 687–692.

Zhang, N., Yang, Y., Huang, L., Xie, H. and Hu, Z. (2019). Birnessite-coated sand filled vertical flow constructed wetlands improved nutrients removal in a cold climate. *RSC advances*, *9*(62), 35931-35938.

Zhang, X., Inoue, T., Kato, K., Izumoto, H., Harada, J., Wu, D., Sakuragi, H., Letsugu, H. and Sugawara, Y. (2017). Multi-stage hybrid subsurface flow constructed wetlands for treating piggery and dairy wastewater in cold climate. *Environmental Technology (United Kingdom)*, *38*(2), 183–191.

Zhu, H., Yan, B., Xu, Y., Guan, J. and Liu, S. (2014). Removal of nitrogen and COD in horizontal subsurface flow constructed wetlands under different influent C/N ratios. *Ecological Engineering*, *63*, 58–63.