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Constructed wetlands in cold-climate regions: performance, challenges, and opportunities: a review

Zonas úmidas construídas em regiões de clima frio: desempenho, desafios e oportunidades: uma revisão

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ABSTRACT

Untreated wastewater discharges into polluted bodies of water jeopardize the availability of water for human consumption. For that reason, constructed wetlands (CWs) are a sustainable and ecological technology commonly used in marginalized communities as an alternative wastewater treatment method, with low installation and maintenance costs. CWs use endemic vegetation for wastewater treatment, similarly to natural wetlands. Pollutants are removed from wastewater through biological, physical, or chemical processes. Additionally, CWs include deep wells, filter medium, and macrophytes. The radicular system of macrophytes decreases pollutant concentration by interacting with microorganisms associated with their roots. Macrophytes are especially important to CWs because they transport oxygen. For this reason, this review outlines the current state of CW technology and its operational challenges under extreme climate conditions, such as cold weather or winter. The operational conditions of CW systems are analyzed, mainly design modifications, macrophyte selection, and environmental conditions. The analysis is based on case studies and the background of CW systems installed in cold-climate regions or operating during the cold season. The review analysis was conducted using “*Methodi Ordinatio*”, which systematically analyzes the information with a specific purpose. Overall, CW systems operating in cold climates are an effective, sustainable, and adaptable technology for wastewater treatment. Effective modifications, such as design adaptations, plant species, and CW type, are essential to optimal operation and to maximize their efficiency.

Keywords: cold season; contaminant removal; macrophytes; plant–microorganism interaction; wastewater treatment.

RESUMO

O despejo de águas residuais não tratadas em corpos d’água poluídos compromete a disponibilidade de água para consumo humano. Por essa razão, a tecnologia de zonas úmidas construídas (ZUC) é sustentável e ecológica, comumente utilizada em comunidades marginalizadas como alternativa para o tratamento de águas residuais, com baixos custos de instalação e manutenção. As ZUC utilizam vegetação endêmica para o tratamento de águas residuais de forma semelhante às zonas úmidas naturais. Os poluentes são removidos das águas residuais por meio de processos biológicos, físicos ou químicos. Por outro lado, a estrutura da ZUC compreende poços profundos, meio filtrante e macrófitas. O sistema radicular das macrófitas é capaz de reduzir a concentração de poluentes por meio da interação com microrganismos associados às raízes. As macrófitas são muito importantes para as ZUC, pois são responsáveis pelo transporte de oxigênio. Por essa razão, esta revisão apresenta o contexto atual da tecnologia de ZUC e os desafios para sua operação em condições climáticas extremas, como clima frio e invernos rigorosos. As condições de operação do sistema de ZUC são analisadas, principalmente em relação à modificação do projeto, à seleção de macrófitas e às condições ambientais. A análise baseia-se em estudos de caso e no histórico de sistemas de ZUC instalados em regiões de clima frio ou operando durante a estação fria. A análise da revisão foi conduzida com o “Método Ordinário”, que analisa sistematicamente as informações com um propósito específico. De modo geral, constatou-se que os sistemas de zonas úmidas construídos (CW) que operam em climas frios são uma tecnologia eficaz, sustentável e adaptável para o tratamento de águas residuais. Modificações eficazes, como adaptações no projeto, na espécie vegetal e no tipo de CW, são essenciais para uma operação ideal e para maximizar sua eficiência.

Palavras-chave: estação fria; remoção de contaminantes; macrófitas; interação planta-microrganismo; tratamento de águas residuais.

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Introduction

Constructed wetlands (CWs) represent a sustainable and cost-effective alternative for wastewater treatment and are widely applied in marginalized communities. These systems mimic natural wetland processes, utilizing interactions between plants, soil, and microorganisms to remove organic matter, suspended solids, pathogens, metals, pesticides, and nutrients through biological, physical, and chemical mechanisms (Postila and Heiderscheidt, 2020; Vega De Lille et al., 2021; Alsubih et al., 2022; Mohamed et al., 2022; García-Ávila et al., 2023; Santos et al., 2024).

A typical CW consists of substrate and vegetation arranged in shallow ponds. Wastewater flows through the substrate and plant roots, where microbial activity facilitates the degradation of organic compounds, nitrogen, and phosphates. CWs are classified according to their hydraulic flow as free flow, superficial flow, vertical flow, horizontal flow, or hybrid systems (Ravikumar et al., 2022; Ferreira et al., 2023; Roa et al., 2023; Carabal et al., 2024; Coelho, 2024; Paruch and Paruch, 2024).

Vegetation, or macrophytes, is central to CW efficiency. Macrophytes can be floating, emergent, or submerged. Plants transport oxygen, enhance microbial activity in the rhizosphere, and contribute to pollutant uptake and degradation. Species are selected based on rapid growth, high biomass, root development, and pollutant removal capacity (Si et al., 2021; Justin et al., 2022; Ravikumar et al., 2022; García-Ávila et al., 2023; Gomes, 2024; Li et al., 2024).

On the other hand, the performance of these systems depends largely on the climate. In tropical and subtropical regions, CWs are highly effective. In colder climates, however, efficiency can drop because of reduced plant and microbial activity. To enhance the efficiency of CWs, modifications to the design, structure, macrophyte type, and substrate are primarily considered (Postila and Heiderscheidt, 2020; Ravikumar et al., 2022; Ferreira et al., 2023; Roa et al., 2023).

As background, Zhang et al. (2019) evaluated vertical-flow CWs with a birnessite cover operating at temperatures near 0°C, achieving an average nitrogen removal of 73.8%. Wang et al. (2018) studied floating CWs at temperatures of -10°C and reported removals of up to 78%; they also characterized the microbial community, finding active nitrifying bacteria in the substrate. Fan et al. (2016) evaluated organic matter and nitrogen removal in a surperficial flow CW in a cold climate, with very high efficiencies even at low temperatures. And Fang et al. (2022) integrated a CW with a bioelectrochemical system operating at 10°C to improve nitrate removal, observing growth of cold-resistant denitrifying bacteria and very high efficiency in total nitrogen (TN) removal.

For that reason, the objective of this review is to analyze the operational challenges of CWs in cold-climate regions by examining specific studies and the factors impacting system efficiency, such as the types of macrophytes used, their interactions with wetland systems, and climate conditions.

Methodology

Theoretical-methodological procedure

This review was conducted using a systematic scientific research method called "*Methodi Ordinatio*", described by Santos et al. (2024). *Methodi Ordinatio* is a research approach that sets out specific criteria to make decisions to select scientific articles for the composition of a bibliographic portfolio. In the first stage of the method, the research focused on wastewater treatment using CWs installed in cold climates. In the next stage, a preliminary search of the defined topic was conducted using the academic databases ScienceDirect, Web of Science, and Scopus. In the third stage, keywords were used to compile articles related to the research topic, such as CWs, wastewater treatment, cold climate, macrophytes, substrate, and pollutant removal, adding the AND operator. In subsequent stages, the bibliographic documentation was filtered, identified, and systematized to form the bibliographic portfolio. These bibliographies were relevant and essential to the discussion. Microsoft Excel® 2021 was used to archive articles, including titles, authors, publication years, scientific journals, and abstracts. SigmaPlot® software was used to create the graphics.

Data analysis

After compiling the bibliographic portfolio, the research focused on publications from 2019 through 2024, as this timeframe encompasses the most significant advances in CW technology and its applications in cold climates. Out of the total articles found, only those that contributed to the aim of this research were included, resulting in 170 articles for analysis, of which 94 articles were selected for reading and constructing the bibliographic portfolio. As illustrated in Figure 1, the topic is relevant to the criteria defined for this study. In 2019 and 2020, 21 and 19 articles were published, respectively. The number increased to 24 in 2021, then decreased to 22 in 2022. The highest number of publications was in 2023, with 38. However, in 2024, the number was reduced to 24 articles.

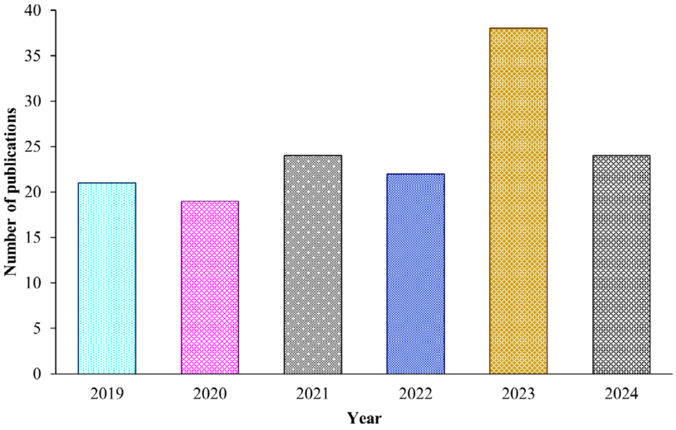


Figure 1 – Evolution of papers published from 2019 to 2024.

State of the art

Types of wastewaters used in constructed wetlands

The effectiveness of CWs depends on wastewater composition. For example, domestic wastewater changes according to consumption habits and has a moderate-to-high organic load, solids, nutrients, and pathogens. In subsuperficial flow wetlands, nitrification and denitrification processes occur, as do nutrient assimilation and solids sedimentation. Furthermore, industrial wastewater has a high organic and nutrient load. In CWs, it must be pretreated to reduce toxicity and prevent carbon saturation. Agricultural wastewater has high nitrate concentrations and, in coastal or arid areas, high salinity. Wetlands can help remove nitrogen (ammonium and nitrate) and phosphorus, reducing dissolved oxygen demand. Salinity and seasonal variability pose challenges. Therefore, salt-tolerant plants are selected, and hydraulic conditions are adjusted. On the other hand, greywater has a lower pathogen load and requires less treatment capacity. In wetlands, greywater can efficiently remove biodegradable materials and nutrients, but it requires longer retention times and a larger system size. Finally, wastewater from landfills has high chemical oxygen demand (COD), ammonium, salts, inorganic compounds, and metals. Although challenging, CWs can effectively treat this type of wastewater, demonstrating their treatment capacity for a wide variety of wastewater (Brunhoferova et al., 2024; Akhiladas et al., 2025; Ofiera et al., 2025; Songkun et al., 2025).

Constructed wetlands for wastewater treatment

CWs are sustainable, low-cost wastewater treatment systems that integrate plant and microbial processes. For that reason, they are considered an integrated ecosystem. They effectively remove organic matter, nutrients, heavy metals, and several pollutants from domestic, industrial, and agricultural wastewater. They are a viable option for small cities and remote communities because of their simplicity, low maintenance, and ecological performance (Sylla, 2020; Roa et al., 2023; Brunhoferova et al., 2024; Paruch and Paruch, 2024; Rani et al., 2024).

Characteristics of constructed wetlands and macrophytes

CWs are engineered ecosystems designed to replicate natural purification processes such as nitrification, denitrification, ammonification, and adsorption, thereby improving water quality. Organic matter degradation occurs mainly through aerobic and anaerobic heterotrophic pathways, complemented by bacterial nitrification–denitrification for the removal of nitrogen and organic compounds (Daniel et al., 2023; García-Ávila et al., 2023; Roa et al., 2023; Santos et al., 2024).

CWs are usually classified based on operational design. Subsuperficial systems comprise vertical, horizontal, and hybrid types. In horizontal flow systems, wastewater goes through the root zone of macrophytes located near the surface. Hybrid systems integrate two wetland types, usually combining superficial and subsuperficial flows, thereby enhancing efficiency and pollutant removal compared to conventional systems. CWs are also classified based on vegetation type. Macrophytes, whether floating, emergent, or submerged, play a crucial role in the efficiency of CW wastewater treatment. They transport oxygen, stimulate microbial consortia in the rhizosphere, and support the degradation of organic matter. Figure 2 shows a visual summary of CW types based on water flow classifications and macrophytes (Ferreira et al., 2023; García-Ávila et al., 2023; Roa et al., 2023; Coelho, 2024; Gomes, 2024).

Factors in constructed wetland operation

Significant factors interfering with CWs include temperature, pH, dissolved oxygen, vegetation type, substrate type, hydraulic retention rate, hydraulic retention time, and water flow. Additionally, design and operation conditions also directly impact system effectiveness. Design has been extensively reported to affect microbial populations and reaction mechanisms for organic matter removal (Gomes, 2024; Rani et al., 2024; Santos et al., 2024).

Substrates play a central role in supporting plant growth, providing nutrients, and interacting with wastewater elements. Alternative materials, such as sugarcane bagasse, have been proposed as effective substrates for enhancing plant development and treatment performance (Sandoval et al., 2019; Varma et al., 2021).

Macrophyte selection is another critical determinant of system efficiency. Species are chosen for their pollutant removal capacity, contribution to denitrification, and tolerance to elevated nutrient and heavy metal concentrations. Climatic conditions further affect plant–microbe interactions, since low temperatures reduce photosynthesis, evapotranspiration, and microbial activity, thereby limiting treatment efficiency (Zhu et al., 2021; Justin et al., 2022; Ravikumar et al., 2022; Ferreira et al., 2023; García-Ávila et al., 2023; Gomes, 2024). The main characteristics of wetland systems and macrophytes are summarized in Figure 3.

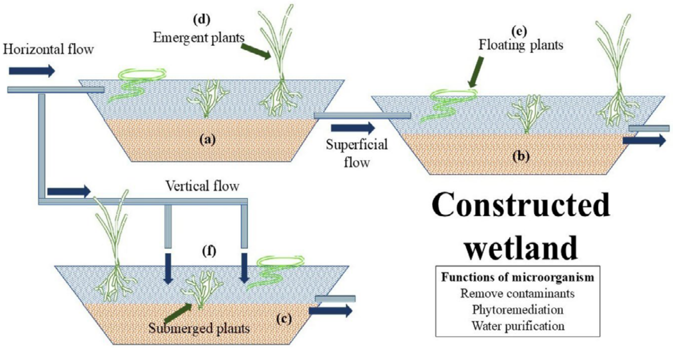
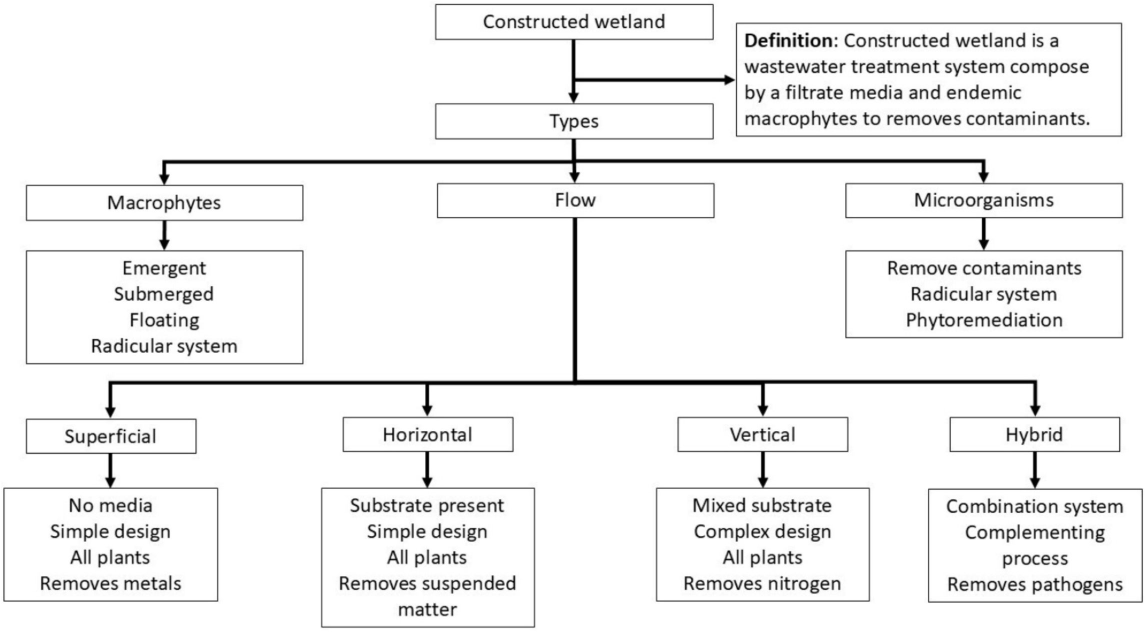


Figure 2 – Constructed wetland classification based on flow design and macrophyte type. (a) horizontal flow constructed wetland; (b) superficial flow constructed wetland; (c) vertical flow constructed wetland; (d) emergent macrophyte; (e) floating macrophyte; (f) submerged macrophyte.



Definition: Constructed wetland is a wastewater treatment system compose by a filtrate media and endemic macrophytes to removes contaminants.

Figure 3 – Constructed wetland characteristics.

Sandoval et al. (2019) note that ornamental plants can remove different types of pollutants during wastewater treatment, in addition to providing economic and social benefits by exploiting these species in commerce. On the other hand, Varma et al. (2021) mention that plant growth is lower at low temperatures, so the efficiency in polluting agent removal is directly affected by climate factors, being the case that CWs operating in cold climates tend to have decreased performance compared to those operating in tropical and subtropical climates.

Constructed wetlands and cold climate

B. Ji (2020) define low temperatures as those below 0°C, which are regularly present during the annual cold season. These temperatures are also observed in high-altitude zones, near mountainous regions, in plains, and in the hemispheres of the planet. Wu et al. (2018) state that cold climates are characterized by temperatures below -3°C that do not rise above 10°C during the day, remaining constant throughout the year, except in the winter, when temperatures tend to decrease to under -20°C. In CWs, temperatures directly impact pollutant removal efficiency by influencing microbial activity. Studies in cold regions like Canada, the northern United States, and China have reported pollutant removal efficiencies of up to 60%, compared to the 90% recorded in tropical climates (Haddis et al., 2020; M. Ji et al., 2020; Liang et al., 2020; Postila and Heiderscheidt, 2020; Rani et al., 2024).

Wu et al. (2018) mention that the effectiveness of CWs operating in cold climates is affected by internal and external design characteristics, and they recommend implementing engineering practices and integrating other emerging technologies. On the other hand, Grebenshchykova et al. (2020) evaluated the efficiency of a modification in the layout of CWs installed in southern Canada, which includes design adaptations and the implementation of artificial aeration systems. In pilot systems, they were successful in removing organic matter up to 91% and total solid removal to 81%, while operating at temperatures reaching -32°C. In the same sense, Varma et al. (2021) mention that modifications mitigate critical aspects such as surface ice formation, hydraulic failures, and malfunctioning of abiotic and biotic compounds. However, random modifications may be counterproductive for their optimal performance. Gomes (2024) noted that temperature is an essential factor for plant development and pollutant removal capacity. For example, at temperatures up to 33°C, plant development decreases and so does their pollutant removal capacity. In turn, at temperatures below 11°C, phosphorus accumulates, causing cyanide toxicity and decreasing the remediation capacity of plants.

Characteristics of constructed wetlands operating in cold climates

CWs can be implemented in cold climates, but their efficiency is generally lower than in warm climates, reaching less than 80% of pollutant removal. Additionally, precipitation contributes to additional humidity and water, which can create hydraulic imbalances and reduce pollution removal efficiency. For this reason, vegetation plays a significant role in regulating these effects, and it interferes with water flow. (Grebenshchykova et al., 2020; Haddis et al., 2020; B. Ji et al., 2020; M. Ji et al., 2020; Postila and Heiderscheidt, 2020; Ferreira et al., 2023).

Several operational parameters regulate the performance of CWs. Among them, the hydraulic loading rate and hydraulic retention time are critical to ensuring adequate contact between wastewater, microbial communities, and substrates. A sufficiently long hydraulic retention time promotes redox stratification and enables the sequential development of microbial processes. pH is also a key parameter controlling microbial activity and, consequently, the efficiency of pollutant transformation. The microbial community involved in nitrification, denitrification, ammonification, and mineralization exhibits pH-dependent metabolic kinetics; slightly acidic conditions may enhance overall nitrogen removal, whereas neutral pH ranges generally favor nitrifying bacteria. The interaction between pH and hydraulic retention time is particularly relevant, as longer hydraulic retention time buffers pH fluctuations, supporting the formation of stable and diverse biofilms. Dissolved oxygen is essential for nitrification and aerobic degradation of organic matter. In subsuperficial flow wetlands, limited oxygen availability highlights the importance of passive or forced aeration and oxygenation via plant tissues, which improve the removal of biochemical oxygen demand (BOD) and COD (Varma et al., 2021; Gomes, 2024).

An important parameter to measure efficiency is the feed flow volume and its distribution along the system. Horizontal flow CWs are inefficient for nitrogen removal, whereas vertical flow CWs show limited denitrification under cold conditions. Hybrid systems, combining vertical and horizontal flows, achieve higher pollutant removal. Free flow CWs, in which water flows naturally toward ponds, are also used in cold regions, typically with emergent macrophytes to support pollutant removal (Grebenshchykova et al., 2020; B. Ji et al., 2020; Vega De Lille et al., 2021).

Substrates contribute to physical pollutant removal and directly influence microbial activity and plant root development. Effective substrates should ensure adequate porosity, surface area, stability, and oxygen circulation. There are two main categories of substrate: traditional (soil, sand, and gravel) and emergent (functional materials such as metals, salts, ashes, or biochar), the latter often combined with traditional substrates (M. Ji et al., 2020; Varma et al., 2021; García-Ávila et al., 2023; Rani et al., 2024).

In summary, the efficiency of CWs in cold climates depends on an intricate balance between system design, substrate selection, microbial activity, and environmental conditions. Hybrid flow systems, emergent substrates, and optimized hydraulic and aeration parameters can mitigate temperature-related limitations, enhance pollutant removal and ensure more stable system performance under adverse climatic conditions (B. Ji et al., 2020; M. Ji et al., 2020).

Effect of climate on constructed wetlands performance

Oxygen transport in CWs is a key factor for system efficiency, as it sustains plant development and microbial activity. Oxygen reaches plants through the roots and leaves during photosynthesis, but low temperatures limit its availability and reduce pollutant removal (Kataki et al., 2021; Vega De Lille et al., 2021; Ravikumar et al., 2022; Gomes, 2024).

Microorganisms play a central role in transforming organic matter and carrying out processes such as nitrification, denitrification, organic nitrogen degradation, and volatilization of compounds. Their activity depends strongly on temperature; in low-temperature regions, heterotrophic bacteria and their microbial activity are limited by organic matter decomposition. Microbial activity is efficient in temperatures ranging from 5 to 40°C, with an optimal range of 20 to 30°C. Below 10°C, microbial activity decreases until it stops at 5°C (M. Ji et al., 2020; Kataki et al., 2021; Varma et al., 2021; Zhu et al., 2021; Ravikumar et al., 2022; Daniel et al., 2023).

Microorganisms have a complex interaction with plants, rhizodeposits, and pollutants. The variation of these interactions depends on the plant species, chemical wastewater composition, ecological demands, and the physical characteristics of the system. Root development slows down between 5–10°C due to restricted oxygen availability, reducing nutrient uptake and negatively affecting assimilation of nitrogenate pollutants. Freezing temperatures further damage cells through ice crystal formation (M. Ji et al., 2020; Justin et al., 2022; Ravikumar et al., 2022).

Plants selected for the system must have optimal adaptation to environmental conditions, a sound radicular system, adequate body hydration, and antifreeze characteristics (M. Ji et al., 2020). There are several species commonly used in CWs for cold-climate regions showing promising results for pollutant removal, such as *Phragmites australis*, *Typha orientalis*, and *Acorus calamus*, mainly (Grebenshchykova et al., 2020; B. Ji et al., 2020; M. Ji et al., 2020; Varma et al., 2021; Justin et al., 2022; Ravikumar et al., 2022; Gomes, 2024).

B. Ji et al. (2020) state that plant species such as *Potamogeton crispus L.*, *Schoenoplectus fluviatilis*, *Bolboschoenus fluviatilis*, *Carex nebrascensis*, and *Carex utriculata* have good performance for a wide variety of pollutant agents. On the other hand, Varma et al. (2021) mention that species of the genus *Typha* can remove up to 72% of COD and up to 71.3% of TN. The species *Phragmites* removes up to 81% of COD and up to 71.6% of TN. The same results are shown with plants *Cyperus payrus* and *Scirpus grossus*.

Ravikumar et al. (2022) mention that plants such as *Eichornia crassipes*, *Salvinia herzogii* and *Pistia stratiotes* can remove metals; plants such as *Myriophyllum spicatum*, *Hydrilla verticillate*, *Potamogeton* spp. and *Ceratophyllum demersum* can eliminate diverse compounds during wastewater treatment. On the other hand, plants such as *Phragmites australis*, *Phalaris arundinacea*, *Typha dominguensis*, *Phragmites karka,* and *Typha latifolia* can eliminate different types of metals.

Gomes (2024) noted that aquatic plants such as *Eichhornia crassipes*, *Elodea canadensis*, *Azolla filiculoides*, *Lemna minor*, *L. gibba*, *Myriophyllum spicatum*, *Pistia stratiotes,* and *Salvinia* have proven their capacity to remove a wide variety of pollutants, the reason why they are commonly used in phytoremediation processes. For example, *E. crassipes*, *L. minor,* and *P. stratiotes* demonstrated high phytoremediation potential for nitrogen and other heavy metal removal, with efficiency of up to 95%.

As shown in Table 1, CW types are compared as to the macrophytes used and their performance in removing the main compounds studied, such as COD and TN concentration. For all cases analyzed, only CWs operating at low temperatures were considered.

Table 1 – Performance of constructed wetland under cold climate conditions.

Constructed wetland type	Substrate	Feed	Macrophyte	Temperature (°C)	Pollutant agent removal (%)		Country	Reference
					COD	TN		
Free	Quartz sand	Domestic wastewater	*Cyperus sp.* *P. paspalodes*	Not determined	89.0	77.0	Turkey	Gunes et al., 2021
Free	Sandy loam soil	Wastewater	*Salix sp.* *Populus spec.*	-33.0 to -15.0 10.0 to 32.0	60.0 68.0	84.0 35.0	Mongolia	Khurelbaatar et al., 2021
Free	Q. rubor Q. rubra	Drained rooftop water	*C. demersum* *E. densa*	20.0±7.0	Not determined	~90.0	Spain	Maceda-Veiga et al., 2022
Free	Not determined	Wastewater treatment plants	*E. crassipes* *P. stratiotes* *L. minor*	20.0	75.0	23.0	Benin	Akowanou et al., 2023
Free	Soil	Wastewater	Not determined	13.0 25.0 to 27.0	Not determined	76.6 to 93.3	Lebanon	Khatib et al., 2023
Free	Gravel	Wastewater treatment plants	*S. lacustris* *M. trifollata* *T. minima* *N. alba* *L. salicaria* *N. idea* *I. pseudacorus* *C. riparia* *T. latifolia* *P. amphibia*	Not determined	83.2	63.8	Italy	Masi et al., 2023
Free	Arable land Mineral soils	Agricultural wastewater	Emergent vegetation	~20.0	Not determined	78.0	Sweden	Nilsson et al., 2023
Free	Gravel	Wastewater	*C. aquatilis* *S. microcarpus* *B. syzugachne* *C. retrorsa* *G. grandis* *J. balticus* *S. validus*	3.4	Not determined	~86.0	Canada	Wilkinson et al., 2023
Free	Gravel	Synthetic wastewater	*S. atrovirens*	15.9	Not determined	90.6 to 94.6	Ethiopia	Angassa et al., 2024
Free	Heavy clay	Wastewater	*G. maxima* *F. ulmaria*	Not determined	Not determined	46.0±16.0	Sweden	Choudhury et al., 2024
Free	Geomaterials (shale or laterite)	Domestic wastewater	*P. purpureum*	25.0 to 33.0	83.0±5.4 76.9±7.0	72.2±10.7 55.5±16.4	West Africa	Traoré et al., 2024
Hybrid	Gravel, sand	Municipal wastewater	*S. miyabaena*	-5.5 to 14.4	81.0	Not determined	Canada	Grebenshchykova et al., 2020
Hybrid	Fine gravel Coarse gravel	Domestic wastewater	*H. psittacorum* *C. isocladus* *Canna sp.* *A. bambusifolia* *A. purpurata*	23.0±2.4	90.0	Not determined	Sweden	Magalhães Filho et al., 2021
Hybrid	Gravel, sand, ashes	Lactic industry wastewater	*P. australis* *Phragmites sp.* *Rice*	6.2	94.0	84.2	Ireland	B. Ji et al., 2020
Hybrid	Volcanic gravel	Pork industry wastewater	*P. australis*	7.3	95.0	70.0	Czech Republic	B. Ji et al., 2020
Hybrid	Rocks, sand	Domestic wastewater	*P. aundinacea* *P. australis*	-25.3	39.0	6.5	Austria	B. Ji et al., 2020
Hybrid	Gravel, Clinoptilolite, tire scraps, oyster shells	Winery industry wastewater	Not determined	20.0	90.0	72.0	United States	Skornia et al., 2020

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Table 1 – Continuation.

Constructed wetland type	Substrate	Feed	Macrophyte	Temperature (°C)	Pollutant agent removal (%)		Country	Reference
					COD	TN		
Hybrid	Not determined	Municipal wastewater	*P. australis* *L. perenne* *T. orientalis*	-1.8 to 15.2	53.0	36.4	Not determined	Varma et al., 2021
Hybrid	Not determined	Pork and dairy wastewater	*P. australis*	5.2 to 7.3	96.0	86.0	Not determined	Varma et al., 2021
Hybrid	Gravel	Domestic wastewater	*S. lancifolia* *T. dominguensis*	Not determined	84.6	70.4	Mexico	Vega De Lille et al., 2021
Hybrid	Gravel, clay	Not determined	*P. australis,* *T. orientalis* *L. salicaria L.* *A. calamus L* *S. trifolia* *Iris wilsonii*	-2.0 to 7.0	40.0	55.5	China	Zhu et al., 2021
Hybrid	Soil mix	Domestic wastewater	*P. australis*	10.5	75.7	46.1	Ireland	Mohamed et al., 2022
Hybrid	Gravel	Municipal wastewater	Not determined	14.0 to 26.0	67.0	84.0	Egypt	Frascari et al., 2024
Hybrid	Not determined	Domestic wastewater	*P. australis* *T. latifolia*	Not determined	58.0	92.7	Slovenia	Zelnik et al., 2024
Horizontal	Zeolite, volcanic rock, gravel	Urban wastewater	Not determined	9.0	Not determined	54.8	China	Liang et al., 2020
Horizontal	Not determined	Wastewater	*P. australis* *T. latifolia*	Not determined	60.2	24.8	Czech Republic	Vymazal, 2020
Horizontal	Clay	Brewery effluent	*C. alternifolius* *T. latifolia*	6.1 to 15.2 24.7 to 30.4	74.0	63.0	Ethiopia	Alayu and Leta, 2021
Horizontal	Gravel	Wastewater	*P. karka* *I. kashmiriana* *S. latifolia*	1.0 to 10.0 37.0 to 46.0	27.9	14.4	India	Qadiri et al., 2021
Horizontal	Not determined	Industrial wastewater	*P. australis*	15.0	Not determined	70.0	Netherlands	Sabri et al., 2021
Horizontal	Not determined	Municipal wastewater	*Salix sp.* *Bryophyte sp.* *H. vulgaris* *Carex species*	-3.4 to 5.0	Not determined	77.3	Not determined	Varma et al., 2021
Horizontal	Not determined	Municipal wastewater	*P. australis* *T. orientalis*	-0.1	60.3	34.5	Not determined	Varma et al., 2021
Horizontal	Not determined	Rural wastewater	*H. lilioasphodelus* *I. tectorum* *O. violácea* *S. erythostictum* *H. ensala*	10.0	79.0	60.0	Not determined	Varma et al., 2021
Horizontal	Not determined	Synthetic wastewater	*P. australis*	10.0	79.0	60.0	Not determined	Varma et al., 2021
Horizontal	Not determined	Primary wastewater treatment	*H. compressa*	17.8 to 18.8 20.7 to 21.6	72.14	Not determined	Pakistan	Javeed et al., 2022
Horizontal	Gravel	Domestic wastewater	*P. australis*	13.7±34.0	82.0	29.0	Egypt	Salem et al., 2022
Horizontal	Gravel Soil Biochar	Agricultural wastewater	*P. australis* *J. maritimus*	20.8±1.2	Not determined	48.0±8.3	Spain	Guerrero-Brotons et al., 2023
Horizontal	Not determined	Wastewater	*P. australis*	4.0	61.4	Not determined	Italy	Mancuso et al., 2023

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Table 1 – Continuation.

Constructed wetland type	Substrate	Feed	Macrophyte	Temperature (°C)	Pollutant agent removal (%)		Country	Reference
					COD	TN		
Horizontal	Coarse gravel Fine gravel	Synthetic wastewater	*I. pseudacorus*	Not determined	90.0±3.0	20.0	United State	Rozman et al., 2023
Horizontal	Gravel	Mix of raw whey rejected by a dairy industry	*P. australis* *T. latifolia* *C. papyrus*	10.0 to 16.0 25.0 to 37.0	80.0	90.4	Tunisia	Mahmoudi et al., 2024
Horizontal	Soil	Wastewater	*Equisetum spp* *Z. aethiopica*	14.0	80.0 to 90.0	80.2	Ecuador	Matovelle et al., 2024
Horizontal	Gravel	Synthetic wastewater	*I. aquatica* *P. neapolitanum*	14.7 to 21.3 21.2 to 29.5	Not determined	12.6	Japan	Nguyen et al., 2024
Superficial	Not determined	School wastewater	*Scirpus validus* *Cyperus papyrus*	17.2 to 22.5	58.0	Not determined	Ethiopia	Haddis et al., 2020
Superficial	Not determined	Wastewater treatment plant	*O. decumbens* *H. verticillate*	15.0 to 20.0	Not determined	48.9	China	Zhao et al., 2020
Superficial	Not determined	Raw olive mill wastewater	*C. alternifolius L.* *V. zizanioides L.*	25.0 to 40.0	Not determined	82.7	Turkey	Goren et al., 2021
Superficial	Not determined	Industrial wastewater	*P. australis*	15.0	Not determined	70.0	Netherlands	Sabri et al., 2021
Superficial	Volcanic rock, pyrite	Synthetic wastewater	*C. indices L.*	6.7	49.1	24.7	China	Si et al., 2021
Superficial	Not determined	Pluvial wastewater	*Scirpus* *Juncus* *Lemna*	-7.8 to -3.8	Not determined	49.0	Not determined	Varma et al., 2021
Superficial	Not determined	Municipal wastewater	*T. orientalis* *P. australis* *S. validus* *I. pseudacorus*	14.3 to 23.2	Not determined	77.0	No determined	Varma et al., 2021
Superficial	Not determined	Agricultural wastewater	*E. canadensis*	Not determined	11.4	40.9	Not determined	Varma et al., 2021
Superficial	Not determined	Domestic wastewater	*Not determined*	22.8	73.0 to 95.0	28.0 to 55.0	Dominican Republic	Pérez et al., 2024
Superficial	Not determined	Synthetic wastewater	*P. australis* *I. pseudacirus*	12.0 to 20.0 9.0 to 16.0	76.4±26.6	88.3±8.9	Poland	Wojciechowska et al., 2024
Vertical	Not determined	Nitrogen and carbon aqueous solutions	*V. zizanioides* *O. sativa*	Not determined	91.0	18.5	Not determined	Almeida et al., 2019
Vertical	Fine gravel Coarse sand	Wastewater	*P. australis*	25.0 to 35.0	97.8	99.5	Oman	Al-Wahaibi et al., 2021
Vertical	Not determined	Municipal and winery wastewater	*T. latifolia*	1.4	98.0	98.0	Not determined	Varma et al., 2021
Vertical	Not determined	Municipal wastewater	*P. australis* *S. miyabeana*	-36.4 to 14.4	74.0	Not determined	Not determined	Varma et al., 2021
Vertical	Not determined	Synthetic wastewater	*P. australis*	-1.0 to 8.0	Not determined	62.8	Not determined	Varma et al., 2021
Vertical	Coarse gravel Fine gravel Sand	Faecal sludge	*B. vulgaris*	20.0 to 28.0 42.0 to 43.0	88.6 to 91.3	71.5 to 81.6	Burkina Faso (Africa)	Osei et al., 2022
Vertical	Soil Gravel	Greywater (synthetic wastewater)	*P. australis*	37.0 to 49.0	93.0	74.0	Kuwait	Alateeqi et al., 2023
Vertical	Coarse gravel Fine gravel Granular activated carbon	Wastewater Concentrated anaerobic sludge	*D. papyrus*	Not determined	94.1±4.9	62.3	Australia	Ebrahimi et al., 2023

Continue...

Table 1 – Continuation.

Constructed wetland type	Substrate	Feed	Macrophyte	Temperature (°C)	Pollutant agent removal (%)		Country	Reference
					COD	TN		
Vertical	WFS Gravel	Not determined	*C. indica* *P. australis*	23.1 to 26.4	63.8	Not determined	Iraq	Faisal and Nasif, 2023
Vertical	Gravel	Wastewater treatment plants	*P. australis*	Not determined	83.2	63.8	Italy	Masi et al., 2023
Vertical	Coarse gravel Fine gravel Sand or vermiculite	Synthetic light greywater	*T. jasminoides* *L. japonica* *C. laevis*	14.8±5.0	96.0±7.0	Not determined	Greece	Stefanatou et al., 2023
Vertical	Sand	Domestic wastewater	Not determined	14.1	Not determined	44.3±28.7	Sweden	Hamisi et al., 2024
Vertical	Not determined	Activated sludge	*P. australis*	Not determined	65.9	89.0	Spain	Hernández-Crespo et al., 2024
Vertical	Not determined	Activated sludge	*I. pseudacorus* *J. subnodulosus*	Not determined	65.4	86.6	Spain	Hernández-Crespo et al., 2024
Vertical	Gravel media	Irrigating wastewater	*I. cylindrical*	22.9 24.5	51.0 40.9	53.9 44.9	Kuwait	Khajah and Ahmed, 2025

Figure 4 shows that COD removal efficiency increases with operating temperature, reaching values above 90% in warm and temperate climates. Under adverse conditions, such as polar climates (<10°C), efficiencies decrease to around 60%, comparable to those reported for cold climates (10–15°C). Vertical flow shows higher efficiency at low temperatures, achieving up to 95% COD removal in polar climates and 80% in cold climates. In contrast, hybrid and superficial flow systems show the lowest values under these conditions. In contrast, in temperate and warm climates, all wetland types exceed 75% efficiency, with maximum values close to 94%.

Regarding nitrogen compound removal, Figure 5 shows the relationship between CW operating temperature and the percentage of TN removal. In general, the five types of wetlands analyzed achieve up to 60% TN removal from wastewater. Under cold climate conditions, removal percentages exceed 70% across all evaluated systems. Similar to COD removal, as temperature increases, so does efficiency. Therefore, CWs installed in warm climates report up to 80% TN removal in most types studied. In contrast, systems operating in temperate climates (16–25°C) show lower performance compared to other temperature ranges. In particular, free flow systems in polar climates exhibit the highest TN removal values compared to other types under similar operational conditions, whereas horizontal flow systems record the lowest efficiencies. In cold climates, most wetland systems exceed 60% TN removal, maintaining similar results under temperate conditions, except for horizontal flow wetlands, which show lower efficiencies under all climate types.

In general terms, CWs demonstrate strong dependence on operating temperature for pollutant removal efficiency. COD removal increases with higher temperatures, exceeding 90% in warm and temperate climates, while efficiencies decrease to 60% under polar conditions. Vertical flow systems outperform other configurations in low-temperature environments, achieving up to 95% removal. Similar to COD removal, TN removal follows a temperature-dependent trend, with efficiency values up to 70% in cold climates and up to 80% in warm climates. Free-flowing systems achieve the highest TN removal across climates with up to 70% efficiency, whereas horizontal flow wetlands consistently report the lowest performance. Overall, CWs maintain removal efficiencies above 60%, confirming their robustness under diverse climatic conditions.

Challenges for constructed wetlands in cold-climate regions

Cold climates impose challenges for wastewater treatment with CWs, because low temperatures reduce biological and physical processes that drive treatment efficiency. Strategies to address these limitations include system insulation, optimized flow configurations (superficial, subsuperficial, or hybrid), and substrate selection to maintain suitable conditions for microbial activity. Such measures enhance system resilience and support consistent pollutant removal even under adverse conditions. These challenges in wastewater treatment through CW technology may be addressed through structural modifications, with a focus on collaboration to minimize the impact of low temperatures, ensuring sustainable treatment.

Several studies have reported the challenges of installing CWs in cold-climate regions or operating during the cold season. Efforts include insulators, design modifications, and installation of appropriate plant species with specific characteristics: fast growth, high biomass generation, capacity to thrive in cold environments, and capacity to grow with high levels of pollutants. For example, Wu et al. (2018) propose feed modifications to improve CW function. B. Ji et al. (2020) propose including thermal insulation, artificial aeration, feed flow, scaling, and other design layouts.

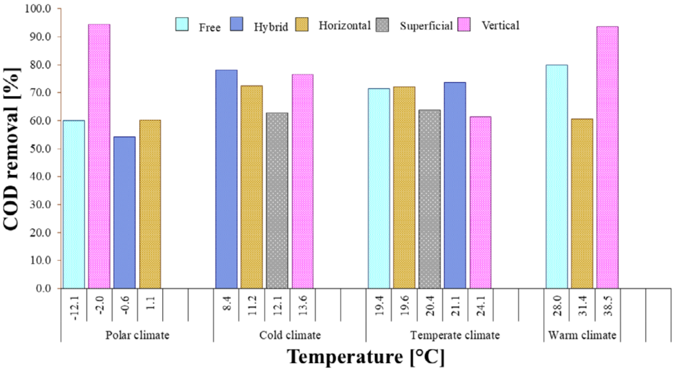

Figure 4 – Relationship of constructed wetlands according to operating temperature and COD removal percentage.

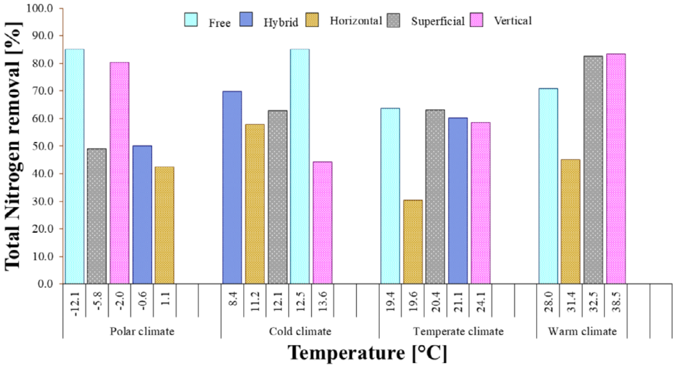

Figure 5 – Relationship of constructed wetlands to operating temperature and total nitrogen removal percentage.

Arliyani et al. (2024) and Soo et al. (2024) propose combining bioelectrochemical processes, such as microbial fuel cells adapted to artificial wetlands for energy production. In this sense, Kataki et al. (2021) mention that the combination of CWs with microbial fuel cells increases efficiency by 49%. On the other hand, Sharma et al. (2023), Arliyani et al. (2024), Soo et al. (2024), and Tyagi and Anand (2024) propose combining with emergent technologies, such as waste stabilization ponds, floating rafts, phytoremediation, phytofilters, dendroremediation, artificial wetlands, bioelectrochemical systems, absorption techniques, foam separation techniques, electrochemical techniques, and advanced absorption processes, for integral wastewater treatment.

Finally, CWs installed in cold-climate regions are crucial for wastewater treatment technology due to their capacity to combine efficiency, sustainability, and adaptability in adverse conditions. Plants play a fundamental role in transporting oxygen, supporting microbial communities, and contributing to pollutant degradation. Beyond treatment efficiency, plants provide resilience and ecological stability, reinforcing wetlands as integrated systems. Overall, CWs in cold regions demonstrate the potential to combine efficiency, adaptability, and sustainability. Structural modifications, appropriate macrophyte selection, and technological integration are essential to ensure long-term functionality, promote water resource sustainability, and protect both ecosystems and public health.

Conclusions

This review highlights that CW performance in low-temperature environments is strongly influenced by vegetation type, system design, and structural adaptations. These systems can achieve 60-80% removal efficiencies depending on wetland type or through the integration of emergent technologies. Unlike other reviews, this manuscript highlights the importance of plant selection and adaptation as key elements for optimizing wetland performance under unfavorable thermal conditions.

One of the main challenges in cold climates is ensuring the permanence and functionality of the selected vegetation. Not all species thrive at low temperatures. For that reason, macrophytes play a critical role in maintaining system functionality because they affect oxygen transport, microbial activity, and pollutant removal, ensuring resilience and system stability. Ornamental and endemic species with fast growth, high biomass production, and tolerance to high pollutant loads are particularly valuable, as they contribute to both aesthetic and functional performance without competing with agricultural or food resources.

Structural adjustments have been implemented to counteract freezing and thermal loss effects, such as the use of insulating materials. In this sense, vertical flow and hybrid configurations generally achieve higher pollutant removal efficiencies. On the other hand, this review shows that COD and NT removal in CWs are strongly influenced by temperature. In polar (<10°C) and cold (10–15°C) climates, COD removal remains above 60%, with vertical flow systems achieving up to 95%. Nitrogen removal reaches 60–70% under cold conditions.

In conclusion, CWs in cold climates are effective, sustainable, and adaptable systems for wastewater treatment. Careful integration of resilient plant species, optimized design, and structural adaptations are required to maximize their efficiency. Future research should focus on enhancing plant resilience, understanding pollutant impacts on vegetation, evaluating the influence of wastewater type on plant tolerance to toxicity, and integrating innovative technologies to maintain high removal efficiencies for organic matter and nutrients under adverse climatic conditions.

Authors' Contributions

Barrales-Fernández, C.: writing – original draft; SANDOVAL SALAS, F.: writing – review & editing, supervision; **Sandoval-Herazo**, L. C.: conceptualization; **López-Méndez**, M. C.: supervision; **Méndez-Carreto**, C.: formal analysis, writing – review & editing.

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