

Constructed Wetlands as a Sustainable Technology for Wastewater Treatment: Current Trends and Future Potential

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1. Introduction to the Special Issue

The world is currently facing a dual challenge of water scarcity and pollution, exacerbated by the rapid development of the social economy and continuous improvements in living standards, which have heightened public concern regarding and the demand for water quality and safety [1]. Globally, approximately 359.4×10^9 m³/year of wastewater is generated, with nearly half being discharged into the environment without adequate treatment [2]. Although conventional wastewater treatment plants (WWTPs) have been widely adopted for water pollution control in many countries, they are often associated with high energy and chemical consumption, limited efficiency in removing emerging contaminants and pathogens, significant greenhouse gas (GHG) emissions [3,4], and a fundamental disconnection from the natural ecosystems they aim to protect. Therefore, there is an urgent need for solutions that are both environmentally sustainable and economically viable.

Constructed wetlands (CWs), also referred to as treatment wetlands, emulate the synergistic interactions among plants, substrates, and microorganisms to efficiently remove pollutants in a controlled environment [5,6]. Recognized as environmentally sustainable, cost-effective, and efficient nature-based solutions, CWs have become increasingly important for wastewater treatment [7]. Similar to natural wetlands, CWs provide a range of ecological and societal benefits, such as water storage, purification, resource recovery, and carbon sequestration [8]. They contribute to urban water management by enhancing rainwater retention and infiltration, supporting climate change mitigation, restoring biodiversity, and serving as venues for environmental education, recreation, and ecotourism [9,10].

The purpose of this Special Issue is to address contemporary challenges in CWs, such as carbon emission reduction and the treatment of emerging contaminants. The collected contributions offer valuable insights derived from diverse research studies, with a focus on advancing innovative applications and enhancing the mechanistic understanding of CWs for effective pollution control and sustainable development.

2. Main Contributions of This Special Issue

This Special Issue comprises seven research articles and four review articles that focus on advancing the design of constructed wetlands, enhancing treatment performance, elucidating the removal and transformation mechanisms of emerging contaminants, and investigating geochemical processes within the context of carbon neutrality.

A comprehensive understanding and optimization of pollutant removal mechanisms in CWs are essential to improving treatment efficiency and ensuring long-term system stability. Nitrogen removal in CWs is primarily driven by microbially mediated nitrification and denitrification processes [contribution 1], whereas phosphorus dynamics are



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largely regulated by the synergistic interactions between plant uptake and substrate adsorption. Long-term monitoring of estuarine CWs has demonstrated average removal efficiencies of 36.2% for total nitrogen (TN), 26.7% for total phosphorus (TP), and 30.7% for the permanganate index (COD_{Mn}). However, prolonged operation may lead to pollutant accumulation and substrate saturation, ultimately resulting in reduced treatment performance [contribution 2]. These findings enhance the mechanistic understanding of pollutant removal in CWs and provide critical data for optimizing system performance and sustaining long-term operational effectiveness.

Synergistic purification mediated by plants and microorganisms plays a pivotal role in enhancing the efficiency of pollutant removal in CWs. Root exudates released by submerged macrophytes have been shown to vary in response to environmental factors such as light intensity and nutrient availability, thereby influencing the composition and structure of microbial communities in both planktonic and biofilm phases [contribution 3]. These shifts in microbial community dynamics directly affect biofilm development and the rates of pollutant degradation. In *Vallisneria*-based wetland systems, optimal TN removal was observed at an air-to-water ratio of 15:1, which coincided with a marked enrichment of aerobic denitrifying bacteria within the biofilm [contribution 4]. Collectively, these findings highlight the essential contribution of plant–microbe interactions to the functional stability and resilience of wetland ecosystems, underscoring the potential of plant-mediated microbial regulation as a sustainable, nature-based strategy for water purification.

Design parameters and site-specific conditions play a critical role in determining the treatment efficiency and ecological functionality of CWs. The effectiveness of ecological buffer zones in intercepting non-point source pollution is jointly influenced by buffer width, vegetation composition, and slope gradient, with nitrogen and phosphorus removal rates reaching up to 90% under optimal configurations [contribution 5]. A study conducted in high-altitude regions of Ecuador demonstrated that surface flow CWs exhibit superior performance compared to vertical subsurface flow CWs in removing organic matter and microbial contaminants, which can be attributed to longer hydraulic retention times (HRTs) and the better adaptation of native plant species [contribution 6]. In contrast, wetlands dominated by low-density *Nelumbo nucifera* may contribute to increased nitrogen accumulation. To enhance denitrification, this study recommends expanding stands of *Phragmites australis* [contribution 7].

Research on CWs has progressively advanced beyond the conventional objective of pollutant removal, expanding to encompass broader evaluations of ecological impacts and system sustainability [contributions 8 and 9]. CW systems employed for swine wastewater treatment have demonstrated significant efficacy in removing suspended solids (SS) and nutrients. However, their operation necessitates strict control of organic loading rates to mitigate clogging risks and minimize emissions of greenhouse gases, particularly nitrous oxide (N_2O) and methane (CH_4) [contribution 10]. In response to these environmental challenges, innovative approaches, such as the integration of microbial fuel cells (MFCs) into CWs, are being investigated to enhance treatment performance while concurrently reducing carbon footprints [contribution 11]. Furthermore, CWs are increasingly acknowledged for their potential in mitigating non-point source pollution originating from agricultural runoff and livestock effluents, especially under adverse conditions such as high altitudes or in cold climates. Nonetheless, these systems continue to face critical challenges associated with fluctuating pollutant loads, climatic variability, and long-term operational reliability, underscoring the need for future designs that balance treatment efficiency with environmental sustainability.

The contributions presented in this Special Issue provide novel insights into the optimization of design, mechanistic understanding, and sustainable application of CWs under

evolving environmental challenges. With ongoing research and practical implementation, CWs are expected to assume an increasingly significant role in pollution control, carbon mitigation, and urban ecological restoration, thereby offering substantial support for the development of water ecosystems that reflect the harmonious coexistence between humans and nature.

Conflicts of Interest: The authors declare no conflict of interest.

List of Contributions:

1. Dong, J.; Kuang, S. Bibliometric Analysis of Nitrogen Removal in Constructed Wetlands: Current Trends and Future Research Directions. *Water* **2024**, *16*, 1453. <https://doi.org/10.3390/w16101453>
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