Plants Do it Better: How Constructed Floating Wetlands Can Improve the Wastewater Treatment Process at Lake County's Southeast Treatment Facility

Thesis

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Abstract

Plant-based wastewater treatment systems leverage natural processes to benefit small, disadvantaged, and remote communities that lack the resources for major facility upgrades. Constructed floating wetlands (CFWs) can be incorporated into wastewater treatment ponds to improve treatment efficiency economically, particularly when robust native aquatic plants with high nutrient uptake are used. The Southeast Treatment Plant in Lake County, CA, has historically struggled to meet the Biochemical Oxygen Demand (BOD) levels stipulated by its Waste Discharge Requirements (WDR) permit. This study aims to evaluate the effectiveness of CFWs in improving wastewater treatment at this facility and to identify plant species that can enhance treatment outcomes.

This paper reviews several international case studies employing macrophytes closely related to or native to those found around Clear Lake, California. The selection of studies was based on their relevance to treating municipal sewage and the use of plant species capable of reducing biological oxygen demand (BOD), nitrogen, phosphorus, total suspended solids (TSS), and total dissolved solids (TDS). Research was conducted primarily through the Sacramento State library's online database, using specific search terms related to wetlands and sewage treatment. Information about the Southeast Treatment Plant was gathered through interviews with the treatment plant operators.

The analysis identified specific plant species with high removal efficiency for various pollutants. *Typha domingensis*, *Brachiaria mutica*, *Canna indica*, *Leptochloa fusca*, *Phragmites australis, Rhaphiolepis indica*, *Ocimum tenuiflorum*, *Hibiscus rosa-sinensis*, and *Chrysopogon zizanioides* showed effectiveness in reducing BOD levels. Additionally, *Typha domingensis*, *Brachiaria mutica*, *Canna indica*, *Leptochloa fusca, Phragmites australis*, and *Rhaphiolepis indica* were noted for their nitrogen uptake capabilities, while *Canna indica* excelled in

phosphorus reduction. *Typha domingensis* and *Canna indica* also demonstrated high removal efficiency for TSS. Furthermore, species such as *Chrysopogon zizanioides*, *Pistia stratiotes*, *Eichhornia crassipes*, *Hydrocotyle umbellata*, *Lemna minor*, *Typha latifolia*, and *Scirpus acutus* were effective in reducing TDS.

The findings highlight the potential for leveraging native and related macrophytes to improve wastewater treatment outcomes at the Southeast Treatment Plant. The use of CFWs can provide a cost-effective and efficient solution for meeting and exceeding WDR requirements, without the need for expensive infrastructure upgrades. Implementing CFWs at the Southeast Treatment Plant can enhance the facility's ability to meet regulatory requirements and improve water quality. By utilizing plant species with proven effectiveness in pollutant removal, the treatment plant can achieve sustainable and economical improvements in wastewater management. This approach can serve as a model for similar facilities facing resource constraints.

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Introduction

Wetlands are often likened to the kidneys of water systems due to their remarkable capacity to filter out various pollutants found in waterways. In recent decades, interest has greatly increased in investigating natural biological systems for purifying water. Both natural and constructed wetlands have garnered attention for their well-established ability to effectively filter out sediments and various pollutants from contaminated water sources (Benvenuti et. al., 2018). Building on these natural filtration processes, wetlands have been successfully integrated into wastewater treatment systems, specifically those using lagoons to treat sewage.

Wetlands function within wastewater lagoons by providing a natural, biological filtration system. They use plants and microorganisms to remove pollutants from the water. Wetland plants absorb harmful nutrients such as nitrogen and phosphorus, which can cause environmental problems in excess. These nutrients are taken up by the plants and integrated into their growth. Meanwhile, microorganisms around the plant roots and in the water break down organic matter and other contaminants, transforming them into less harmful substances. By harnessing these natural processes, wetlands can significantly improve the efficiency of wastewater treatment, making them an effective and sustainable solution for managing wastewater.

One such facility that could greatly benefit from these advancements is the Southeast Wastewater Treatment Plant in Lake County, California. Over the past five years, this plant has faced significant challenges in meeting its waste discharge requirements (WDR) permit. Specifically, between May 2021 and March 2023, the plant experienced 12 violations for exceeding the Biochemical Oxygen Demand (BOD) limits established by its permit (California, 2024). Given these ongoing compliance issues, incorporating wetlands into the plant's wastewater treatment processes could provide a practical solution. By leveraging the natural filtration capabilities of wetlands, the Southeast Treatment Plant could enhance its ability to manage BOD levels, improve overall water quality, and better align with regulatory standards.

Lake County Special Districts Southeast Treatment Plant

The Southeast wastewater treatment plant is situated just north of the City of Clearlake in Lake County, CA. It handles the collection and treatment of wastewater across a wide area in the Clearlake region, extending from Pirates Cove to Lower Lake and encompassing the City of Clearlake. As outlined in the 2022 Sewer Master Plan, this system serves a population of approximately 13,176 residents or 8,094 Single Family Dwelling (SFD) equivalents. However, due to the Clayton fire in 2016, the Sulphur fire in 2017, and the Cache Fire in 2021, the number of household connections in the Southeast collection system has been reduced (LCSDA, 2022).

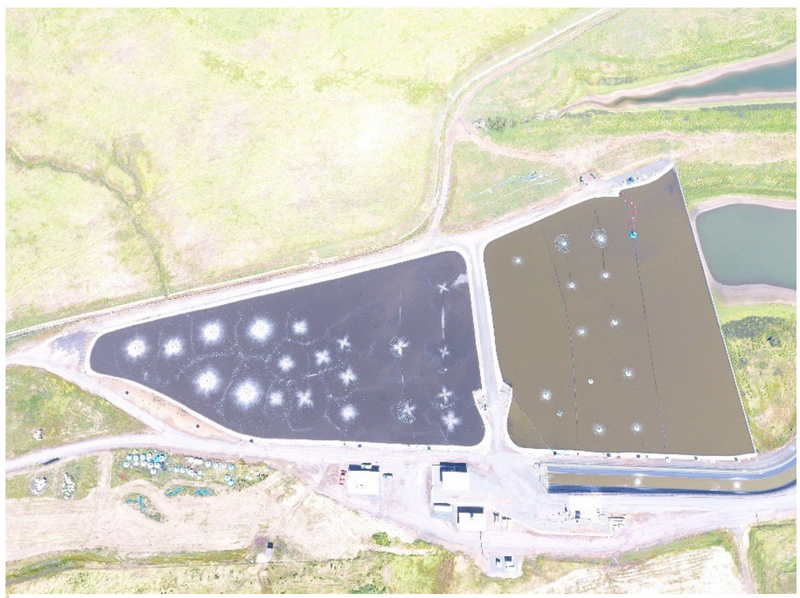

Figure 1) An aerial photo of the north and south pond at the Southeast Wastewater Treatment Plant in Lake County, CA. The north pond is on the left and the south pond is on the right (Eric Luna, 2024).

Unfortunately, the treatment plant has faced significant operational challenges in the past. In 1996, the plant received a Cease-and-Desist order due to frequent sewage spills. To address this issue, Lake County Special Districts constructed two new facultative lagoons for wastewater treatment in 1997. Originally, these lagoons were designed with aerators and curtains, creating fully mixed and partially mixed cells in each lagoon. With a freeboard of 2 feet, the Southeast treatment plant has a capacity of 17.7 million gallons (MG), with the North Pond holding 8.8 MG and the South Pond holding 8.9 MG.

Issues with the Southeast Treatment Plant

In 2013, the operators at the Southeast Treatment Plant initiated equipment changes in the two facultative lagoons. They replaced the original aerators with Blue Frog aerators, which required the removal of the existing pond curtains. (Fisher, 2024). Consequently, the fully mixed and partially mixed cells in each lagoon were eliminated. Interestingly, it's worth noting that in the 2022 Sewer Master Plan for the Southeast Facility there is no mention of the Blue Frog units. Despite the removal of the curtains and the change in the aeration system, the Southeast facility continues to report their water sample results as being from cells, even though the curtains that created the cells have been absent for 10 years (LCSDA, 2022)

Unfortunately, the Blue Frog units proved unsuitable for treating sewage at facilities like the Southeast plant. Over their decade of operation, they struggled to deliver adequate dissolved oxygen (DO), leading to the buildup of a substantial sludge layer. Engineered for the treatment

Figure 2) (a) (left) Image of the Blue Frog aerators that are used at the Southeast Treatment Plant. (b) (right) Image of the Blue Frog aerators being used in the south pond at the facility (Eric Luna, 2024).

of shallow aerobic lagoons, the Blue Frogs lacked the necessary flow dynamics for the Southeast plant's two facultative lagoons. This resulted in insufficient oxygenation being distributed through the aerobic and facultative zone of the Southeast lagoons. Consequently, ammonia oxidation was impeded, precipitating a notable increase in BOD (Fisher, 2024).

The elevated ammonia levels further exacerbate the surge in BOD by serving as a nutrient source for specific microorganisms. With heightened ammonia concentrations, these microorganisms undergo rapid proliferation, driving increased microbial activity in the water. As they metabolize organic substances, oxygen depletion occurs, further elevating the BOD levels.

In 2021, operators at the plant decided to start returning the plant back to its original design (Fisher, 2024). Unlike many other wastewater treatment plants, the Southeast facility does not release its treated wastewater into nearby water bodies. Instead, the treated wastewater undergoes a unique process where it is pumped to the Geyser's Geothermal Field to generate electricity. Here, the water is injected into the ground near magma chambers to produce steam, which in turn spins turbines for electricity generation. Notably, the 26-mile pipeline transporting the water is exempt from the Chapter 15, Title 23, California Code of Regulations, Section 2510. This exemption is due to several factors: 1) the California Regional Water Quality Control Boards have issued waste discharge requirements to the Southeast Treatment Facility, 2) the discharger is in compliance with the basin plan, and 3) the effluent is classified as non-hazardous (LCSDA, 2022). However, it's essential to note that if the Southeast Plant operates in violation of its WDR Permit, then the effluent in the pipeline would also be considered in violation.

Constructed Floating Wetlands

Constructed floating wetlands (CFWs) have emerged as a promising and innovative technology for addressing stormwater, agricultural runoff, and municipal sewage. Although their design and setup are relatively simple, studies have shown that CFWs are highly effective in improving the quality of sewage effluent (Ijaz et al., 2015). Numerous studies demonstrate that CFWs efficiently remove substantial amounts of nutrients and pollutants from different water sources. Utility districts globally are embracing CFWs for their cost-effectiveness and effective water filtration abilities. Additionally, water agencies in low-income countries favor CFWs because they are cost-effective, energy-efficient, and have a low environmental impact (Benvenuti et. al., 2018).

In CFWs, macrophytes serve as the primary biological element, playing a crucial role in pollutant removal. They not only directly absorb pollutants into their tissues but also promote purification processes by increasing environmental diversity around the root zone. This fosters various chemical and biochemical reactions, thereby improving purification processes. Additionally, many macrophytes possess bioaccumulative properties, further aiding in pollutant removal (Benvenuti et al., 2018; Ijaz et al., 2015).

Figure 3) These are both images of constructed floating wetland systems (Martin Ecosystems; Atlan Stormwater).

CFWs offer a potentially cost-effective solution for aiding in the wastewater treatment process at Lake County's Southeast Wastewater Treatment Plant. Numerous studies have explored the use of CFWs in sewage treatment. However, comparing these studies proves challenging due to the diverse variables involved. Each study incorporates different factors such as inflow rates, sewage composition, and local environmental conditions. Typically, these studies begin by creating mesocosms using the same effluent received by the wastewater treatment plant.

They then test various combinations of native plants to determine the most effective species or combination for larger-scale applications.

Despite extensive research in this area, no study has specifically investigated the potential benefits of CFWs at the Southeast Wastewater Treatment Plant. Additionally, no wastewater treatment facility in the Sacramento Region currently utilizes CFWs in facultative ponds (Fisher, 2024). As a result, the feasibility of implementing this technology at the Southeast Treatment Plant remains unexplored.

Goals and Objectives

The objective of this thesis is to showcase the potential application of CFWs in facultative ponds in California, along with advocating for a mesocosm study to evaluate the filtration capability of bulrushes in untreated sewage. Currently, no wastewater treatment facilities in the Sacramento region utilize CFWs (Fisher, 2024). Clear Lake harbors numerous native aquatic plants, including several different species of bulrush, which have been the subject of many studies investigating its filtration effectiveness in sewage. This paper analyzes existing field studies to provide insights and recommendations for improving the design and implementation of CFW installations, aiming to enhance understanding and promote wider acceptance of these wastewater treatment systems.

Various case studies employing CFWs for municipal wastewater treatment were examined, including those employing different species of native grasses, sedges, or bulrushes. Wastewater sampling records from March and April were obtained from the Southeast Treatment Plant. Although comparing different CFW implementations worldwide poses challenges due to substantial variability between facilities, hypotheses and inferences can be formulated by analyzing case studies that utilize similar plant species and their outcomes from treating municipal sewage.

Methods

Background: Construction of Floating Treatment Wetlands (CFWs)

When selecting the type of material to be used for constructing CFWs, several factors such as buoyancy, durability, and ecological compatibility must be considered. Different studies around the world have employed various materials and designs tailored to their specific needs and conditions. Utility districts in economically stronger regions may have more financial resources to invest in higher-quality materials for these platforms. At the upper end of the scale, utility districts can opt for floating units made of polyethylene. These units resemble modular plastic docks and provide enough buoyancy for utility workers or researchers to walk on them (Wilkinson et al., 2023). Alternatively, more budget-friendly options include square mats made of polyester fiber injected with polystyrene foam (Park et al., 2019).

Material Selection

In Novo Hamburgo, Brazil, a buoyant structure was utilized to support emergent vegetation, primarily consisting of macrophytes like *Typha domingensis*. These structures facilitated hydroponic growth, enabling the plants to absorb nutrients straight from the water column (Benvenuti et al., 2018). In Islamabad, Pakistan, a phytoremediation garden was established using earthen ponds, creating a sequential system for wastewater treatment. This natural approach utilized the existing terrain and water bodies to treat wastewater effectively (Farid et al., 2014). Faisalabad, Pakistan, utilized floating mats made from Diamond Jumbolon-Board, a commercially available non-cross linked polyethylene material. This choice was driven by the board's durability, moisture barrier, temperature tolerance, and affordability. The ease of installation, with just the need for drilling holes, made it an optimal choice for establishing floating wetlands (Ijaz et al., 2015; Afzal et al., 2019). Rio Grande, Brazil, opted for floating structures made from recycled polypropylene with polyethylene floating buoys. These structures provided ample space for plant growth while being environmentally friendly by utilizing recycled materials (Bauer et al., 2021). Hamilton, New Zealand, employed interwoven polyester fiber mats with polystyrene foam patches for buoyancy. These mats were ultra-violet resistant and designed to withstand environmental conditions for prolonged periods, providing stability and support for plant growth (Park et al., 2019). Arakkonam, India, utilized floating rafts made of naturally buoyant bamboo for cultivating plants in their CFW process. Bamboo's inherent buoyancy and sustainability made it an ideal choice for this application (Arivukkarasu & Sathyanathan, 2023). In Alberta, Canada, plastic modules were retrofitted into stabilization ponds, each containing multiple crates with plants. This modular approach allowed for flexibility in design and installation, adapting to the specific requirements of the treatment site (Wilkinson et al., 2023).

Plant Species Selection

In the selection process plant species are carefully chosen based on their capacity to take up nutrients and pollutants from wastewater, along with their compatibility with floating wetland habitats. In Novo Hamburgo, Brazil, *Typha domingensis* is favored for sewage treatment due to its effective removal and breakdown of contaminants through various mechanisms (Benvenuti et al., 2018). Similarly, in Islamabad, Pakistan, aquatic plants like *Pistia stratiotes, Eichhornia crassipes*, and others are employed for wastewater remediation (Farid et al., 2014). In Faisalabad, Pakistan, plants such as *Brachiaria mutica, Canna indica*, and *Typha domingensis* are selected from local sources for their resilience and rapid growth, ideal for phytoremediation in challenging environments (Ijaz et al., 2015; Afzal et al., 2019). Likewise, *Typha domingensis* is favored in Rio Grande, Brazil, for its ability to accumulate nutrients and support microbial communities (Bauer et al., 2021). Other regions, like the University of Western Australia and Taxila, Pakistan, choose plants based on their effectiveness in constructed wetlands and adaptability to local conditions (Zhang et al., 2007; Shah et al., 2015). Additionally, factors like local availability and climate adaptability are considered in the selection process, as observed in Arakkonam, India, and Heraklion, Crete, Greece (Arivukkarasu & Sathyanathan, 2023; Fountoulakis et al., 2017). Overall, these carefully chosen plant species play a vital role in enhancing CFW performance by efficiently removing pollutants from wastewater and ensuring the sustainability of treatment systems.

Soil and Matrix Selection

In Faisalabad, Pakistan, floating mats made of Jumbolon-Board support hydroponic roots without the need for additional substrate (Ijaz et al., 2015; Afzal et al., 2019). Similarly, in Hamilton, New Zealand, polystyrene foam serves as the buoyant material for hydroponic roots, again without a substrate (Park et al., 2019). In the University of Western Australia, sands are used as a substrate, capable of adsorbing nutrients to some extent (Zhang et al., 2007). Conversely, in Ilha Solteira, Brazil, and Taxila, Pakistan, free-floating aquatic macrophytes do not require a matrix (Anjos et al., 2019; Shah et al., 2015). In Fazenda Agua Limpa, Brazil, gravel #2 acts as a support medium for the plants (Sandri & Reis, 2021). Arakkonam, India, uses plastic net pots to support the plants without any soil or growth medium (Arivukkarasu & Sathyanathan, 2023). In Alberta, Canada, plant seedlings are planted in crates layered with 10 cm of gravel (Wilkinson et al., 2023). In Heraklion, Crete, Greece, a combination of coarse gravel at the front and effluent end of the bed, along with finer gravel in the main bed, supports vegetation at varying depths (Fountoulakis et al., 2017). Finally, in Kenilworth, Australia, scoria gravel is used in planting media baskets to support plant tube stock during early growth phases (Huth et al., 2021). In CFWs, the absence of substrates or matrices is due to their design for hydroponic operation. In hydroponic setups, plants grow directly in water, bypassing the need for soil or solid mediums; their roots absorb nutrients directly from the aquatic environment. The construction of the wetland matrix varies depending on the needs of the plant species and the site's environmental conditions.

Biofilm Enhancements

In many studies, it is emphasized that promoting biofilm growth around the roots of plants on CFWs is vital for efficient pollutant removal. This biofilm, made up of fungi, bacteria, and beneficial algae, clings to the roots and rhizomes, acting as a natural filter to remove contaminants (Benvenuti et al., 2018). Additionally, the microenvironment created around the plant roots provides an ideal habitat for microbes, aiding in the removal of different pollutants (Ijaz et al., 2015; Afzal et al., 2019). In Hamilton, New Zealand, artificial biofilm support media are incorporated into the wetland base to offer more surfaces for biofilm attachment, especially in systems processing organic wastewater that has elevated levels of oxygen and nutrients. This addition helps overcome challenges like reduced root length and density beneath CFWs, possibly enhancing the rates of nitrification and denitrification (Park et al., 2019). Macrophytes play a role in oxygenating the effluent mass, encouraging the development of a thick layer of biofilm containing microorganisms in the roots, which serve as a filter for pollutants (Sandri & Reis, 2021). In Kenilworth, Australia, the roots of plants in CFWs reach down into the water beneath the floating structure, providing ample surface area for microbial biofilm growth, akin to a hydroponic system (Huth et al., 2021). These strategies collectively enhance biofilm growth around plant roots, thereby improving the overall efficiency of pollutant removal in CFWs.

Data Collection

Each case study was chosen for its relevance to treating municipal sewage and addressing pollutants similar to those managed by the Southeast Treatment Plant. Additionally, the selected studies utilized plant species that are native or related to those found in Lake County. Sacramento State library's online database was almost exclusively used for locating peer reviewed articles. The search terms and their variations included: 'domestic sewage treatment,' 'constructed floating wetlands (CFWs),' 'floating treatment wetlands,' 'wastewater treatment,' 'natural wastewater treatment,' 'Schoenoplectus validus,' 'Typha domingensis,' 'nutrient removal,' 'nitrogen and phosphorus removal,' 'wetland plant management,' 'macrophytes,' 'aquatic plants,' 'plant species selection,' 'plant nutrient uptake,' 'water quality,' and 'wetland plants.' Articles not related to domestic sewage or phytoremediation were excluded based on their titles and abstracts. Furthermore, a detailed review of the methods sections was conducted to assess the relevance of plant species and the study setup. To gather information about the Southeast Treatment Plant, interviews with the plant operators were conducted. These interviews focused on the facility's operations and the parameters contributing to the past regulatory violations.

Results and Findings

Case Study Findings:

Novo Hamburgo, Brazil:

In Novo Hamburgo, Brazil, a sewage treatment plant conducted a test to assess the effectiveness of a constructed floating wetland (CFW) in removing pollutants and nutrients from wastewater. They used a species of aquatic plant called *Typha domingensis* for this purpose. The study involved placing the CFW over an existing tank at the wastewater treatment facility. Over the course of one year, they monitored how well the CFW performed in removing various pollutants from the sewage. Parameters such as chemical oxygen demand (COD), 5-day biochemical oxygen demand (BOD), and total suspended solids (TSS) were measured to evaluate the removal of organic matter. The results indicated significant reductions in COD (55%), BOD (56%), and TSS (78%). Moreover, nutrient levels were notably decreased, with total Kjeldahl nitrogen (TKN) dropping by 41% and total phosphorus by 37%. The floating mats effectively supported the growth of the plants without any issues. This study highlights the potential of CFWs as an effective and economically viable alternative for sewage treatment in Brazil. (Benvenuti et al., 2018).

Islamabad, Pakistan:

The experiment took place at the National Institute of Bioremediation (NIB), situated within the National Agricultural Research Center (NARC) in Islamabad, Pakistan. Pakistan has faced significant challenges related to water scarcity and pollution over the years. Since 1947, the country has been grappling with water shortages. Improperly discarding domestic and industrial wastewater has had negative impacts on human health, the environment, and agricultural output. Around 26% of Pakistan's agricultural land is being irrigated with domestic and industrial wastewater. To address these issues, A phytoremediation garden was set up, incorporating different types of aquatic plant species including *Pistia stratiotes, Eichhornia crassipess, Hydrocotyle umbellatta, Lemna minor, Typha latifolia*, and *Scirpus acutus*. These plants were grown in seven pond systems made of earthen materials. The results of the study demonstrated significant improvements in water quality parameters following treatment. Specifically, electrical conductivity (EC) was reduced by 33.7%, turbidity (measured in NTU) decreased by 93.1%, Nitrate was reduced by 77.6%, and total dissolved solids (TDS) were lowered by 35.2%. The study concluded that employing sequential phytoremediation using a combination of plant species proved to be more effective compared to relying solely on a single plant species. This indicates the potential of using a diverse array of plants in phytoremediation efforts to address water pollution and scarcity issues in Pakistan (Farid et al., 2014).

Faisalabad, Pakistan

This experiment took place in the Chokera neighborhood of Faisalabad, Pakistan. CFWs were installed on wastewater stabilization ponds to assess how well a full-scale CFW system performed over a three-year period. The wastewater treatment plant in this area of Faisalabad deals with effluent from various industries as well as municipal sewage waste. This results in elevated concentrations of organic, inorganic, and microbial contaminants in the wastewater. Because the facility could not meet water quality standards, residents became concerned. Species such *as Brachiaria mutica, Canna indica, Leptochloa fusca, Phragmites australis, Rhaphiolepis indica,* and *Typha domingensis* were collected from nearby drains, canals, and wastewater ponds. The species *Rhaphiolepis indica* and *Canna indica* were purchased from a local market as well as grown in a nursery. These plants were chosen based on their ability to reduce pollution, their root systems, water cleaning capabilities, how well they fit into the landscape, and their adaptability to the local environment. The FTWs led to notable improvements in water quality indicators and lowered the levels of heavy metals in the wastewater. The system achieved impressive removal rates, such as 79% for COD, 88% for BOD, and 65% for TDS. This study emphasizes that CFWs are an environmentally friendly solution for managing sewage and industrial wastewater treatment on a large scale. (Ijaz et al., 2015; Afzal et al., 2019).

Perth, Australia:

This experiment took place at The University of Western Australia in Perth. For this experiment researchers gathered effluent from a nearby wastewater treatment plant. In Australia, treated sewage is released into rivers, estuaries, or oceans after undergoing secondary treatment, however, it may still contain nitrogen and phosphorus, which have the potential to induce eutrophication in the bodies of water where it's discharged. The aim of this research was to assess the efficiency of two types of plants, *Canna indica* and *Scripus validus*, in eliminating nitrogen and phosphorus from laboratory-simulated municipal wastewater treated in small-scale wetland environments. The findings revealed that both plant species effectively removed nutrients, reducing nitrogen by 62–87% and phosphorus by 35–55%. The main mechanism for nutrient removal in the wetland microcosms was identified as plant uptake. When the two plant species were grown together in a mixed culture, there was not a significant improvement in nutrient removal compared to when they were grown separately as monocultures. This lack of improvement was attributed to competition between the two species. Overall, the study underscored the importance of plant nutrient uptake in the removal of nitrogen and phosphorus in constructed wetlands (Zhang et al., 2007).

Alberta, Canada

The study took place at a facultative cell stabilization pond that serves the Violet Grove community, situated near Drayton Valley in Alberta, Canada. The facility discharges its treated wastewater biannually into a natural waterway that eventually links up with the North Saskatchewan River. For the research, seven species of aquatic plants were selected due to their potential for phytoremediation, their natural presence in the area, ease of cultivation, and availability from local sources. These included *Carex aquatilis, Scirpus microcarpus, Beckmannia syzigachne, Carex retrorsa, Glyceria grandis, Juncus balticus,* and *Schoenoplectus tabernaemontani* (also known as *Scirpus validus*).

The findings showed that Scirpus microcarpus exhibited the greatest accumulation of nitrogen, phosphorus, sulfur, and calcium in its roots compared to other species. In shoots, *Schoenoplectus tabernaemontani* showed the highest accumulation of nitrogen, phosphorous, sulfur, and calcium. *Scirpus microcarpus* also had the highest calcium accumulations among all species. This research highlights the advantages of using simple, nature-based methods for treating wastewater, especially in smaller and isolated communities. By adding a CFW to existing waste stabilization ponds, the treatment process can be significantly improved without requiring high-tech solutions. (Wilkinson et al., 2023).

Arrakonam, India

This study took place in Arrakonam, India, with the aim of exploring treating household wastewater with a floating raft made of naturally buoyant bamboo and a variety of land-based plants like *Canna indica, Ocimum tenuiflorum, Hibiscus rosa-sinensis,* and *Chrysopogon zizanioides*. The effectiveness of these plants in removing pollutants was evaluated through experimental investigations conducted in mesocosms. The findings indicated that *Canna indica* demonstrated the most effective removal of pollutants like TSS at 96%, total phosphorus at 98%, ammonia at 95%, and dissolved oxygen (DO) at 45%. On the other hand, *Chrysopogon zizanioides* exhibited maximum removal efficiencies for turbidity (90%), TDS at 48%, total nitrogen at 85%, sodium at 53%, potassium at 74%, total phosphorus at 92%, EC at 27%, COD at 93%, BOD at 95%, and coliforms like *Escherichia coli* at 47%. The research findings suggested that *Canna indica* and *Chrysopogon zizanioides* were the most efficient land-based plants for removing various nutrients and contaminants from municipal sewage. The research demonstrates that using floating wetland systems with land-based plants could serve as a viable substitute for conventional wastewater treatment approaches. These systems were proven to be sustainable, affordable, and simple to manage, making them feasible options for regions with restricted resources (Arivukkarasu & Sathyanathan, 2023).

Pollutant Removal:

BOD Removal

Firstly, the plants present within CFWs have a vital function in absorbing and processing organic matter, including substances contributing to BOD, as part of their natural growth processes. This phytochemical uptake process involves the transfer of organic pollutants from the water to the plant tissues, where they are either stored or broken down into less harmful forms.

Moreover, the root systems of these plants create an ideal environment for the growth of biofilms, which consist of microbial communities attached to plant roots and submerged surfaces. These biofilms serve as natural filters, aiding in the breakdown and elimination of organic contaminants, including those responsible for BOD, through enzymatic reactions and microbial metabolism.

Additionally, the physical structure of CFWs, including the plant roots and rhizomes, serves as a physical barrier, trapping suspended solids and organic particles from the water column. This physical filtration process contributes significantly to the decrease in BOD and other organic pollutants within the wastewater. Specific plant species, such as *Typha domingensis, Brachiaria mutica, Canna indica, Leptochloa fusca, Phragmites australis, Rhaphiolepis indica, Ocimum tenuiflorum, Hibiscus rosa-sinensis,* and *Chrysopogon zizanioides,* have been found to be particularly effective in reducing BOD levels in wastewater. These plants exhibit varying capacities for phytochemical uptake, biofilm formation, and physical filtration, contributing to their overall effectiveness in pollutant removal in CFW systems (Benvenuti et al., 2018; Ijaz et al., 2015; Afzal et al., 2019; Arivukkarasu & Sathyanathan, 2023).

Nitrogen Removal

CFWs play a significant role in removing nitrogen from wastewater through various processes. One primary mechanism involves the uptake of nitrogen compounds, such as ammonium and nitrate, by the plant roots present in the wetland. Plants like *Typha domingensis, Brachiaria mutica, Canna indica, Leptochloa fusca, Phragmites australis,* and *Rhaphiolepis indica* have been observed to effectively uptake nitrogen from the water column, storing it in their tissues in an organic form. This uptake process helps to reduce the nitrogen concentration in the wastewater, contributing to overall nitrogen removal (Benvenuti et al., 2018; Ijaz et al., 2015; Afzal et al., 2019; Wilkinson et al., 2023).

Additionally, CFWs create favorable conditions for biochemical processes like nitrification and denitrification, which further aid in nitrogen removal. In the nitrification process, oxygen, often supplied by plant photosynthesis, promotes the conversion of ammonium into nitrate under aerobic conditions. The presence of aerobic and anaerobic environments within a wetland's matrix facilitates both nitrification and denitrification processes. Denitrification, which takes place in oxygen-deprived conditions, transforms nitrate into nitrogen gas, which is subsequently emitted into the atmosphere, effectively removing nitrogen from the system.

Furthermore, in some cases, volatilization contributes to nitrogen removal, particularly through NH3 volatilization favored by high pH levels. However, in situations where pH levels are lower than 7, as observed in some studies, volatilization may be less significant. Instead, losses of nitrogen are more likely attributed to denitrification processes (Zhang et al., 2007).

The removal of nitrogen from wastewater also indirectly contributes to the reduction of BOD. Nitrogenous compounds, such as ammonia and nitrate, can serve as electron acceptors in microbial respiration processes. When these compounds are removed from the wastewater through plant uptake or microbial processes like denitrification, the demand for oxygen in microbial metabolism decreases. Consequently, lower nitrogen levels lead to reduced oxygen demand, resulting in lower BOD levels in the wastewater.

Phosphorus Removal

CFWs employ various mechanisms to remove phosphorus from wastewater, contributing to improved water quality. One significant process involved in phosphorus removal is precipitation with soil particles and minerals like calcium, iron, and aluminum. This process is particularly important in wetlands and is favored by different environmental conditions. For example, under aerobic and slightly acidic to neutral conditions, phosphorus is absorbed by iron, whereas in anaerobic environments, absorption by calcium and magnesium is preferred, particularly in slightly basic to neutral pH conditions (Benvenuti et al., 2018).

Moreover, in CFWs, the roots suspended in the water play a crucial role in physically removing phosphorus from the water. This removal can occur through two main processes: biosynthesis and settling. Biosynthesis involves the incorporation of phosphorus into the plant tissue, contributing to its removal from the water. Settling, on the other hand, is the primary process for phosphorus removal and involves the settling of phosphorus-containing particles due to rhizofiltration, where suspended roots physically filter out particles from the water (Benvenuti et al., 2018).

Additionally, biofilms consisting of fungi, bacteria, and beneficial algae that adhere to plant roots and submerged surfaces, contribute to phosphorus removal through their metabolic activities. While there's continued discussion regarding whether phyto-uptake or biofilm metabolism is the primary factor in nutrient removal within CFW systems, it is evident that both processes play significant roles in phosphorus removal (Benvenuti et al., 2018).

Furthermore, in some cases, phosphorus may be removed through precipitation, absorption onto clay particles, conversion to metal phosphate, or reduction through biological processes, such as microbial activity or plant absorption (Afzal et al., 2019).

Research has also shown the efficacy of particular plant varieties, such as *Canna indica*, in removing phosphorus from wastewater. For example, in Arrakonam, India, *Canna indica* showed a remarkable reduction in total phosphorus concentration within a relatively short period, highlighting its potential for phosphorus removal in CFW systems (Arivukkarasu & Sathyanathan, 2023).

Total Suspended Solids Removal

CFWs can efficiently eliminate TSS from wastewater by using both physical filtration and biological mechanisms. In Novo Hamburgo, Brazil, studies have shown that TSS was reduced by approximately 78% with the use of *Typha domingensis* in their CFWs (Benvenuti et al., 2018). The removal mechanism primarily involves settling and the physical trapping and retention of particles within the root-biofilm network found in the wetland system. As wastewater flows through the CFW, flow velocities decrease in the pond-like basin, allowing suspended solids to settle out. Additionally, the hanging root-biofilm network acts as a physical filter, trapping suspended particles as water passes through it (Benvenuti et al., 2018). The effectiveness of TSS removal in CFWs depends on the size and characteristics of the solids contained in the wastewater. Similarly, in Arrakonam, India, CFWs, particularly those utilizing *Canna indica*, demonstrated a high removal efficiency for TSS, reaching up to 96.46% compared to other plant species (Arivukkarasu & Sathyanathan, 2023). This high removal efficiency is attributed to multiple processes, including sedimentation, biofilm development on macrophyte roots, and entrapment of suspended solid particles. The biofilms formed on the roots of macrophytes act as natural filters, capturing suspended solids as water flows through the wetland. These trapped particles may then either precipitate to the bottom of the wetland or be decomposed by microbial action through processes like adsorption. Additionally, natural factors such as oxidation and the native function of microbial communities contribute to the reduction of TSS in the water column (Arivukkarasu & Sathyanathan, 2023).

Total Dissolved Solids Removal

CFWs play a significant role in reducing TDS in wastewater through various physical and biological processes. In Islamabad, Pakistan, a study including species such as *Pistia stratiotes, Eichhornia crassipess, Hydrocotyle umbellatta, Lemna minor, Typha latifolia,* and *Scirpus acutus* demonstrated a reduction in TDS levels by 35.2% (Farid et al., 2014). Notably, *Eichhornia crassipess,* and *Pistia stratiotes*, demonstrated higher effectiveness in reducing TDS compared to others. This reduction is attributed to the salt uptake capacity of these plants, leading to a decrease in TDS concentration in the water column. The overall reduction in TDS levels indicates the effectiveness of CFWs in improving water quality by removing dissolved solids.

Similarly, in Arrakonam, India, experiments with CFWs showed a considerable decrease in TDS levels over time (Arivukkarasu & Sathyanathan, 2023). The combination of physical and biological processes facilitated by floating wetlands aids in decreasing both TDS and TSS in wastewater. Elements like oxidation, adsorption, and the inherent activities of microbial populations all play crucial roles in reducing TDS levels in the water column. Specifically, *Chrysopogon zizanioides* demonstrated a maximum TDS removal efficiency of 48.79%, highlighting the effectiveness of this plant species in mitigating dissolved solids from wastewater.

Overall, the combined effects of plant uptake, physical filtration, microbial activity, and natural processes contribute to the reduction of TDS in wastewater treated by CFWs, making them valuable tools for enhancing water quality and reducing pollutant loads in aquatic environments (Farid et al., 2014; Arivukkarasu & Sathyanathan, 2023).

Discussion

Discussion of Findings:

The case studies offer valuable perspectives on the efficiency of constructed floating wetlands (CFWs) in treating wastewater across different geographical locations, each presenting unique challenges and solutions. Comparing and contrasting their approaches and outcomes offers valuable lessons for potential applications at the Southeast Wastewater Treatment Plant.

In Novo Hamburgo, Brazil, the study demonstrated the efficacy of *Typha domingensis* in pollutant removal, showcasing significant reductions in chemical oxygen demand (COD), biological oxygen demand (BOD), total suspended solids (TSS), total Kjeldahl nitrogen (TKN), and total phosphorus (Benvenuti et al., 2018). This highlights the potential of CFWs in addressing diverse pollutants in wastewater. Similarly, in Islamabad, Pakistan, the utilization of various aquatic plant species led to improvements in water quality parameters, including reductions in electrical conductivity (EC), turbidity (NTU), nitrate, and total dissolved solids (TDS) (Farid et al., 2014). The study emphasizes the importance of employing a combination of plant species for enhanced phytoremediation outcomes, showcasing the versatility of CFWs in different contexts. In Faisalabad, Pakistan, the implementation of CFWs demonstrated notable improvements in water quality indicators, with significant reductions in COD, BOD, and TDS (Ijaz et al., 2015; Afzal et al., 2019). This underscores the potential of CFWs as eco-friendly solutions for large-scale sewage treatment facilities, particularly in areas with high organic and inorganic pollutant loads. In Perth, Australia, their study highlighted the effectiveness of CFWs in nutrient removal, with plant uptake identified as the primary mechanism for nitrogen and phosphorus reduction (Zhang et al., 2007). This suggests the feasibility of using CFWs for nutrient mitigation in secondary-treated municipal wastewater. Furthermore, in Alberta, Canada, the research emphasized the advantages of using nature-based methods, showcasing the potential of CFWs in smaller and isolated communities for wastewater treatment (Wilkinson et al., 2023). This suggests that CFWs can serve as cost-effective and sustainable solutions, particularly in remote areas. Lastly, in Arrakonam, India, the study demonstrated the efficacy of terrestrial plants in pollutant removal, indicating the feasibility of using floating wetland systems with land-based plants as substitutes for conventional wastewater treatment approaches (Arivukkarasu & Sathyanathan, 2023).

Discussion of Constructed Floating Wetlands (CFWs):

The findings from these case studies suggest that CFWs offer versatile and effective solutions for wastewater treatment, with the potential to address various pollutants and water quality challenges. At the Southeast Wastewater Treatment Plant, the fluctuating TSS removal and past violations with BOD highlight the need for a robust and adaptive approach to wastewater treatment. Considering the success of CFWs in addressing similar challenges in other locations, integrating CFWs, particularly those utilizing native plant species belonging to the genus *Scripus* or *Typha*, could enhance the plant's overall treatment efficiency. By harnessing the natural remediation capabilities of CFWs and tailoring them to local conditions, the Southeast Treatment Plant can optimize its wastewater treatment processes, improve effluent quality, and mitigate environmental impacts effectively.

Aquatic macrophytes utilized in wastewater treatment must possess specific traits like rapid growth, high biomass generation along with the capability to gather nutrients and heavy metals without causing harm over extended periods. (Farid et al., 2014). Introducing effective water purification plants outside of their native habitats could pose risks to local ecosystems, potentially affecting agriculture, aquaculture, and biodiversity in the area. (Ijaz et al., 2015). CFWs offer advantages such as direct nutrient uptake, prevention of algal reproduction, resilience to water-level fluctuations, and erosion control, making them cost-effective alternatives for wastewater treatment plants (Chen et al., 2016). CFWs effectively remove suspended solids and enhance sedimentation conditions, facilitating the filtration and degradation of organic matter (Chen et al., 2016). Studies show that BOD and COD removal rates in CFWs increase with hydraulic retention time (HRT), with higher influent concentrations leading to higher BOD removal rates (Chen et al., 2016). However, randomly placing CFWs within retention ponds may reduce treatment efficacy by promoting short-circuiting of flows (Lucke et al. 2019). Circulation and aeration improve the removal kinetics of pollutants in sewage, emphasizing the significance of these procedures in improving treatment efficiency (Zimmels et al., 2009).

Challenges and Considerations

CFWs are not universally applicable to all wastewater ponds. Smaller aerobic ponds with brief retention periods don't provide CFWs enough time to effectively remove nutrients from the wastewater. Additionally, these smaller ponds may lack the space needed to install a CFW system. For example, at Lake County's Northwest Treatment Plant, three small aerobic ponds precede two larger facultative ponds. The limited space and short retention times of these smaller ponds would prevent the effective operation of CFWs (see Figure 4).

Figure 4) An aerial photograph of Lake County's Northwest Wastewater Treatment Plant. On the right side are the three aerobic ponds. On the left side are the two facultative ponds (Fisher, 2024).

Another challenge with CFWs is vegetation. Accumulated plant debris can elevate nutrient levels in the pond, so it's crucial to balance sufficient plant growth with the control of excessive debris (Thullen et al.). Additionally, the use of native plants is strongly encouraged, as non-native species have the potential to spread into and disrupt the surrounding environment. To prevent these issues, it is essential to conduct mesocosm studies using native macrophytes and the specific effluent characteristics of the Southeast Treatment Plant. Such studies would provide valuable evidence for making informed decisions before any significant investment in CFW technology occurs.

While there is extensive information on CFWs, testing methods and mesocosm studies vary by location. Each facility differs in size, effluent volume, composition, and climate, which affects plant growth and treatment efficiency. Despite these variables, most studies have tested for similar pollutants, used comparable plants, and focused on domestic sewage. The consensus from existing research indicates that CFWs are effective in treating domestic sewage. However, to further advance the understanding and application of CFWs, future research should focus on optimizing their design for California's environmental conditions and verifying their performance in a range of different settings.

Conclusion

The Southeast Treatment Plant has had issues as recently as 2023 with biological oxygen demand (BOD) levels exceeding the limits allowed in its waste discharge requirements (WDR) permit. This means that the concentration of organic pollutants in the influent wastewater is higher than what the treatment process can effectively handle. BOD is a metric used to quantify the amount of dissolved oxygen that microorganisms need to break down organic materials in water. Elevated levels of organic pollutants in wastewater can lead to high BOD values. These pollutants can come from various sources, including domestic sewage, industrial effluents, and agricultural runoff. High BOD levels indicate a higher demand for oxygen by microorganisms during the decomposition of organic matter.

When wastewater with high BOD enters the treatment plant, microorganisms begin to metabolize the organic pollutants, consuming dissolved oxygen in the process. If the BOD load exceeds the capacity of the treatment system, it can lead to rapid depletion of oxygen levels in the wastewater, potentially causing anaerobic conditions in certain parts of the treatment process.

A BOD problem can result in incomplete degradation of organic pollutants during treatment. If the treatment process is unable to cope with the high BOD load, it may lead to reduced treatment efficiency and poor removal of organic contaminants from the wastewater. This can result in lower-quality effluent being discharged into receiving water bodies.

High BOD levels in discharged effluent can have detrimental effects on aquatic ecosystems. When organic pollutants are not adequately treated, they can deplete oxygen levels in receiving water bodies, leading to conditions such as hypoxia or even anoxia, which can harm aquatic organisms and disrupt the balance of the ecosystem.

At the Southeast Treatment Plant, there are significant challenges stemming from high levels of BOD. To address these challenges effectively, Constructed Floating Wetlands (CFWs) utilizing native species of *Scripus* and *Typha* offer a targeted solution. By deploying these wetlands, the Southeast Treatment Plant can focus on mitigating specific pollutants such as nitrogen, total suspended solids (TSS), and total dissolved solids (TDS) present in the wastewater. This focused approach enables the Southeast Treatment Plant to enhance its pollutant removal capabilities and improve the overall quality of the treated effluent.

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Appendix

CLEAR LAKE MACROPHYTES

Scientific Name	Common Name	Habitat	Native/Exotic
Arundo donax	Giant Cane	Emerged	Exotic/Invasive
Azolla filiculoides	Mosquito Fern	Floating	Native
Azolla mexicana	Water Velvet	Floating	Native
Ceratophyllum demersum	Coontail	Submerged	Native
Chara sp.	Muskgrass	Submerged	Native
Egeria densa	Brazilian elodea	Submerged	Exotic/Invasive
Eleocharis palustris	Spikerush	Emerged	Native
Elodea canadensis	American Elodea	Submerged	Native
Heteranthera dubia	Water Stargrass	Submerged	Native
Hydrilla verticillata	Hydrilla	Submerged	Exotic/Invasive
Hydrocotyle ranunculoides	Water pennywort	Floating	Native
Hydrodictyon	Waternet	Floating	
Lemna minor	Common Duckweed	Floating	Native
Ludwigia peploides	Creeping water primrose	Submerged	Exotic/Invasive
Myriophyllum aquaticum	Parrotfeather	Submerged	Exotic/Invasive
Myriophyllum spicatum	Eurasian watermilfoil	Submerged	Exotic/Invasive
Myriophyllum sibericum	Northern milfoil	Submerged	Native
Najas flexilis	Slender Water Nymph	Submerged	Native
Najas guadalupensis	Southern naiad	Submerged	Native
Nuphar polysepala	Yellow Water lily, Spatterdock	Floating	Native
Nymphaea sp.	Water lily	Floating	Native
Phragmites australis	Common Reed	Emerged	Native
Polygonum amphibium	Smartweed	Emerged	Native
Polygonum hydropiperoides	Water pepper	Emerged	Native
Potamogeton americanus	American/long leaf pondweed	Submerged	Native
Potamogeton crispus	Curly-leaf pondweed	Submerged	Exotic
Potamogeton gramineus	Variable-leaved pondweed	Submerged	Native
Potamogeton illinoensis	Illinois pondweed	Submerged	Native
Potamogeton natans	Floating-leaved pondweed	Submerged	Native
Potamogeton nodosus	American pondweed	Submerged	Native
Potamogeton pectinatus	Sago pondweed	Submerged	Native
Potamogeton richardsonii	Richardson's pondweed	Submerged	Native
Potamogeton zosteriformis	Flat-stem pondweed	Submerged	Native
Sagittaria montevidensis	California arrowhead	Emerged	Native
Salix gooddingii	Gooding's Black Willow	Riparian	Native
Salix exigua	Sandbar Willow	Riparian	Native

Salix lasiolepis	Arroyo Willow	Riparian	Native
Salix laevigata	Red Willow	Riparian	Native
Scirpus acutus	Tule, Hardstem bulrush	Emerged	Native
Scirpus californicus	Southern bulrush	Emerged	Native
Scirpus validus	Softstem bulrush	Emerged	Native
Typha angustifolia	Southern Cattail	Emerged	Native
Typha domingensis	Narrow leaf Cattail	Emerged	Native
Typha latifolia	Common Cattail	Emerged	Native
Riparian plants that can spend all of their life out of water			
Apocynum androsaemifolium	Dog Bane	Riparian	Native
Cephalanthus occidentalis	Button Bush	Riparian	Native
Cyperus spp.	Sedges	Riparian	Native
Equisetum spp.	Horsetail/Scouring Rush	Riparian	Native
Himalaya and cutleaf blackberry	Rubus spp.	Riparian	Exotic/Invasive
Tamarix spp.	Tamarisk	Riparian	Exotic/Invasive

Table 1) List of native and invasive macrophytes in Clear Lake, CA. This table was provided by the Lake County Water Resources Department (De Palma-Dow, 2010).

Figure 5) This is an aerial photograph looking south at the Southeast Treatment Plant. In the front is the north pond, followed by the south pond, and then discharge reservoir (Eric Luna, 2024)