First stage Project Report
on

DEVELOPMENT OF ECO-CENTRIC TREATMENT OF DOMESTIC WASTEWATER AIMED AT CIRCULAR ECONOMY OF DECENTRALISED WATER REUSE FOR ACADEMIC CAMPUS

Submitted in the partial fulfilment of the requirement for the Degree of

B.Tech.-M.Tech. in Environmental Science and Engineering

by

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APPROVAL SHEET

This seminar report entitled "**Development of eco-centric treatment of domestic wastewater aimed at circular economy of decentralised water reuse for Academic Campus**" prepared by **Abhishek M. Sanas** (Roll No. 18D180001) is hereby approved for submission.

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Comments of Supervisor and Co-supervisor (if any):

Abhishek worked systematically and sincerely in the later part of his preparation period while developing this First stage Project Report. He has a great scope for improvement and I have judged him to be a person who will show much more organized efforts and progress the next time. He has a potential to do well. If he decides and shows more commitment, he will shine.

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ABSTRACT

There is a growing need for more sustainable wastewater treatment technologies to provide non-conventional water sources. Wetlands be it constructed, or natural offers cheaper and low-cost alternative technology for wastewater treatment. Constructed wetlands are engineered, man-made ecosystems similar to natural wetlands to treat wastewater. They have a shallow depression in the ground with a bottom which is levelled. The flow in the constructed wetlands is controlled so that the water is spread evenly among the plants in the wetlands. When we compare the constructed wetlands with natural wetlands, 90% of the water flows through small channels in natural wetlands. This control allows natural processes to occur and more efficient cleaning of wastewater. A constructed wetland system is specifically engineered for 'Water Quality Improvement System'. Constructed wetlands are natural wastewater treatment systems that provide simple and effective wastewater treatment. Domestic, industrial, mining and agricultural wastewaters can be treated using constructed wetlands. Comparing construction costs with conventional systems, they are approximately 50-90% less, and their operating costs are also very low. Constructed wetlands offer the best alternatives for a decentralized water reuse for a limited area.

The current review provides insight into constructed wetlands and its characteristics with focus on the wastewater treatment systems associated with domestic wastewater and the removal characteristics for the system.

Keywords: Eco-centric; Constructed Wetlands; Wastewater Treatment; Circular Economy; Domestic Wastewater; Water Reuse.

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LIST OF ABBRIEVATIONS

CW - Constructed Wetlands

BOD – Biochemical Oxygen Demand

COD – Chemical Oxygen Demand

HSF – Horizontal Subsurface Flow

VSF – Vertical Subsurface Flow

VF – Vertical Flow

HF – Horizontal Flow

SF – Subsurface Flow

FWS – Free Water Surface

SSF – Subsurface Flow

N – Nitrogen

SS – Suspended Solids

P - Phosphorous

ET – Evapotranspiration

HLR – Hydraulic Loading Rate

HRT – Hydraulic Retention Time

TKN – Total Kjeldahl Nitrogen

TP – Total Phosphorous

TSS – Total Suspended Solids

VSS – Volatile Suspended Solids

TN – Total Nitrogen

SFHCW – Subsurface Flow Hybrid Constructed Wetlands

ICW – Integrated Constructed Wetlands

HCW – Hybrid Constructed Wetlands

As – Arsenic

Zn – Zinc

MP – Maturation Pond

DO – Dissolved Oxygen

C/N – Carbon/nitrogen

USEPA – United States Environmental Protection Agency

Chapter 1

Introduction

1.1 Background

Eco-centrism can be defined as a nature-centred system of values. Stan Rowe who is a geo-ecologist and environmentalist from the University of Nebraska, once quoted, " The eco-centric argument is grounded in the belief that, compared to the undoubted importance of the human part, the whole ecosphere is even more significant and consequential: more inclusive, more complex, more integrated, more creative, more beautiful, more mysterious, and older than time." (Rowe, 1994). Eco-centrism finds inherent (intrinsic) value in all of nature. The visionary Earth Charter in 2000 strongly advanced an eco-centric worldview, urging in Principle 1a that we: recognise that all beings are interdependent and every form of life has value regardless of its worth to human beings. (MAHB, 2017). Ecocentrism reminds us that all life is interdependent and that both humans and nonhumans are dependent on the ecosystem processes that nature provides. To conserve biodiversity as a whole, an anthropocentric conservation ethic alone is inadequate. Leopold evocatively called it "the odyssey of evolution" in the context of us being the latecomers in the evolutionary understanding, which is ecocentrism. The logic that we defined will lead to both empathy for our fellow inhabitants and also humility, since in this process we are not too dissimilar from other species. Ecology has a different way of teaching humility since we have no idea about the world's ecosystems and never will.
The following figure gives us a figurative comparison between two crucial perspectives: Anthropocentrism and Ecocentrism

Identifying the differences between anthropocentrism and ecocentrism will help us understand wastewater treatment methods and how they can be put into these different perspectives and improved upon. Let us take an example of the current practices of wastewater treatment methodologies: An average person generates 70-140 litres of wastewater while considering a family of 5, 300-700 litres of wastewater is generated every day. We can generalise that around

100,000 Litres Per Day of wastewater is produced in a normal society. The alarming situation nowadays is that household or domestic wastewater travels through an open-close drainage system to reach either the wastewater treatment plant or the main drains. A considerable amount of manpower and money are needed to carry out these processes, which is quite difficult to afford for society. This results in a considerable amount of wastewater getting untreated, which simultaneously causes severe problems for nearby people when it flows through open drains in the city.

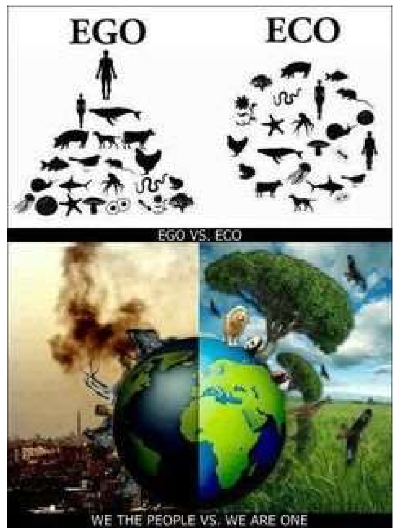

Figure 1.1 Anthropocentrism vs. Ecocentrism (Pinterest, 2022)

The following table gives us a brief idea of the difference between anthropocentrism, biocentrism, and ecocentrism.

Table 1.1 Difference between anthropocentrism, biocentrism and ecocentrism. (Pediaa, 2021)

ANTHROPOCENTRISM	BIOCENTRISM	ECOCENTRISM
Anthropocentrism is the view or belief that human beings are superior to all other organisms.	Biocentrism places greater importance on living components of the environment.	Ecocentrism is a perspective that places importance on the ecosystem as a whole.
Focus on humans.	Focus on all living things.	Focus on the ecosystem as a whole.
Considers human beings the most important	Considers biotic factors necessary	Considers both biotic and abiotic factors important.

The table gives us a fair bit of information about the difference between the three types of ethical perspectives.

The standard treatment systems involve advanced machinery, electricity, and more significant manpower to collect and treat the wastewater, which affects the budget of the wastewater recycling process. It can be concluded that the eco-friendly wastewater treatment system can bring great relief. These treatment systems require three major components (Cleantechwater, 2021): High Operational Costs, Electricity energy and Trained and Qualified staff.
Even if the requirements are met, it is not necessary that it will bring a 100% solution to the problem related to large-scale wastewater treatment. Hence, the eco-friendly solution for wastewater treatment could be the best option to go by.

The benefits of natural wastewater treatment can be divided into two main aspects: Simplicity and, Efficiency and Reliability. The natural wastewater treatment plants can be built near society, and the construction designs of these plants are very simple. The maintenance costs get reduced since it requires low building, and only needs to have a sufficient amount of land near the society for the plant. The natural process of wastewater treatment is very effective for removing harmful contaminants from the water; the only condition is that the efficiency depends on the climatic conditions. A wide variety of solids, contaminants and organic feed can be absorbed by the natural wastewater treatment system even in extreme operating conditions.
There are several other benefits to using a natural wastewater treatment system. The following are some of the main benefits (Cleantechwater, 2021): No need for large space for the set-up of the plant; Controls coliform bacteria; The plant can be set near the society, so the wastewater is not carried through open drains; The filter media and typed of machinery used in the plant are natural; No requirements for contaminants and chemical ingredients for removal; A skilful and qualified person is not required for its operation; The foul odour is suppressed by the plant; Little requirement of electricity for the plant; Sludge is not produced; Reduction in maintenance cost; No causes to flies and mosquitoes; The natural process of wastewater treatment indulges in physical and biological treatment. The treated water can be reused for toilet flushing, car washing, watering plants in gardens/lawns, etc.

Ecological Wastewater treatment relies on bacteria which involves the natural circulation of plants and animals instead of chemicals and mechanical systems. All Wastewater Treatment Systems use living organisms for breaking down biological and chemical waste while traditional or ecological treatment plants use concentrated bacteria to decompose waste in many aeration tanks partially. After this, many chemicals are used for sludge settling and wastewater disinfection. The ecological wastewater treatment plants work in a similar and general way with the difference being the utilisation of varied amount of biological systems like algae, swamp plants, shellfish, worms, oceanic plants, molluscs and vertebrates-supporting the populaces of microscopic organisms that break down squanders and dispose of supplements from the wastewater. This environmental community makes the frameworks steadier within the confront of sudden dosages of intensely sullied water, known as shock flows. (Netsolwater, 2020).

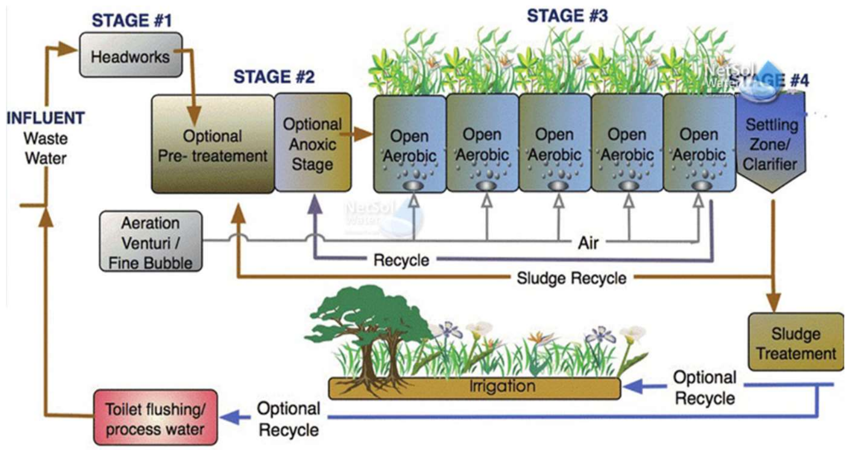

Figure 1.2 Ecological Wastewater Treatment Plant (Netsolwater, 2020)

Figure 1.2 gives a rough idea of how a general ecological wastewater treatment plant function. The treatment plant starts with stage 1 which is like a tank where raw sewage flows in from the expansion tank, this is the place where sand accumulates, and for stimulating biological activity bacteria are sown. For pre-treatment, the anaerobic reactor may or may not be used depending on the strength of the wastewater. The wastewater then flows through a series of ventilated reactor tanks or silos which are connected in series with wastewater inflow under the influence of gravity. To avoid failure in transport these series tanks typically have several parallel trains for increment in dwell time and redundancy. A layer of aquatic plants is seen floating on top of each tank like a mini-ecosystem often supported by a mesh net. (Netsolwater, 2020a)

Most of the work of breaking down waste is done by the extensive root system of these plants which spreads into the water providing habitat for bacteria. Algae, small crustaceans, snails and higher animals are also supported by the tank. The tanks seen in the later part of the series are usually designed for higher organism ecosystems. The water then flows into the purifier, where sludge gets accumulated. Some of the solids which are the sludge can be removed and used to inoculate incoming wastewater with bacteria. The rest is then removed for storage, composting, or land use.

The performance of this ecological sewage system can be evaluated by calculating BOD^5 and COD. These systems are generally effective in reducing BOD and are more permanent in the results. In the first stage of the ecological wastewater treatment systems, aerobic nitrifying bacteria converts ammonia into nitrite and nitrate. In the following second stage, anaerobic denitrifying bacteria convert nitrates to molecular nitrogen (N_2) and release it into the atmosphere. (Netsolwater, 2020a)

Many types of ecological treatment systems have been tried and implemented but constructed wetlands are well known among them for many factors such as cost-effective and environmentally acceptable ecotechnology for contaminated water rehabilitation, particularly in rural and decentralised populations (Pandey, 2022)

1.2 Scope and Objectives

Reclaiming wastewater has a special role in the mitigation of the growing water scarcity threat. Among the available technologies that can contribute to attaining a proper quality of reclaimed water, CWs may have a special role due to their eco-efficiency, low-cost implementation and operation, flexibility, and link to sustainable development and circular economy. Through a review of published work on the production of reclaimed water by CWs in the last decade, combined with a recent review on examples of full-scale reclaiming plants based on CWs, it was observed that most research and field work focus on the use for irrigation or environmental applications, and, mainly, in reclaiming domestic and urban wastewaters. Using other types of wastewater, such as greywater, stormwater, and industrial wastewaters may represent an opportunity to explore CWs implementation. There is still also a need to focus the research on the treated water quality pertaining to these end uses, and a need to standardize reclaimed water regulations and CWs design and operation. Incorporating circular economy approach will help mitigate this need for water scarcity for domestic uses and reduce the burden on water resources and area under the CWs will become self-sufficient.

The specific objectives of this study are as follows:

Objective 1: To study constructed wetlands as the eco-centric treatment system for domestic wastewater

> **Task 1.1**: To study various types of eco-centric domestic wastewater system and constructed wetlands and its different characteristics (substrates, wetland vegetation, microorganisms, hydrology)
>
> **Task 1.2**: To study classification of constructed wetlands and the different treatment methods and the effluent characteristics for its types

Objective 2: Assess the design and construction characteristics of constructed wetlands for the domestic wastewater treatment

> **Task 2.1**: Performing a sampling analysis for assessing substrate, wetland vegetation and micro-organisms requirements for constructed wetlands for domestic wastewater
>
> **Task 2.2**: Determining design considerations (Volume, surface area, soil parameters, wetland vegetation, Hydrology characteristics)

Objective 3: Explain the circular economy approach for constructed wetlands for domestic wastewater and decentralised water reuse

> **Task 3.1**: To study domestic wastewater treatment and its reuse potential in different areas and the impact on society
>
> **Task 3.2**: To investigate the effluent standards and determine its usability in different purposes according to the standard values
>
> **Task 3.3**: Developing inputs for investigating circular economy approach using the effluent treated water from the CWs for household purposes

1.3 Organisation of Report

Chapter 2 gives us a brief introduction about constructed wetlands, its characteristics, design considerations and its various types. Chapter 3 explains the treatment methods and efficiency for domestic wastewater as a review and removal performance. Chapter 4 acts as a conclusion to the literature review with summary and future direction for the study

Chapter 2

Constructed Wetland Treatment Systems

2.1 Introduction

Decision-makers were under pressure from the deteriorating water quality to enact strict rules and discover new, affordable water treatment technologies to maintain a healthy ecological environment (Forslund et al., 2009). To increase and improve water quality, constructed wetlands are a cheap and efficient natural treatment method (Al-Hadidi, 2021) and lessen eutrophication in general (S. Jitvimolnimit and Sirianuntapiboon, 2007; Greenaway, 2001). Since the 1950s, artificial wetlands have been used to treat various types of wastewater, including acid mine drainage, urban runoff, municipal, industrial, and waste from agriculture. These artificial wetlands simulate natural wetland systems' biological, physical, and chemical processes Vymazal (2011). According to Moreira and Dias (2020), constructed wetlands provide an "eco-friendly" alternative to traditional secondary and tertiary municipal and industrial wastewater treatment methods. In many developing nations, constructed wetlands are quickly gaining popularity and becoming a helpful water resource management approach (Al-Hadidi, 2021).

To develop a sustainable and effective treatment system based on a complex natural ecosystem, constructed wetlands for wastewater treatment have replaced traditional wastewater treatment procedures and goals (Hammer, 2020). In emerging nations, wetland treatment technology for wastewater has a lot of promise and offers a competitive edge over traditional, mechanical treatment methods. It is economically possible, offers ecological balance, and has a high level of self-sufficiency (Galbraith et al., 2005).

The most common type of artificial wetland is a basin with water, substrate material, and vascular plants. These elements can be used to build a wetland (Vymazal, 2010). Additionally, wetlands have naturally growing aquatic invertebrates and microbiological ecosystems (Vymazal, 2010). In artificial wetlands, the water spreads evenly among the plants and the flow is controlled. Constructed wetlands are highly flexible and may be built in almost any place and under various conditions, mimicking the ideal treatment conditions found in natural wetlands (Batool and Saleh, 2020). Wastewater flows through a porous material like gravel or on top of the existing soil in the constructed wetland (subsurface wetland). Various mechanisms have been proposed in engineered wetlands systems, and they are frequently interconnected. (Al-Hadidi, 2021) lists many of these mechanisms: Resolving a specific matter that was suspended in PM; Filtration and chemical precipitation when wastewater touches substrate litter and plants; Pollutants are changed chemically; Ion exchange and adsorption on the plant, substrate, sediment, and litter surfaces; Microorganisms' degradation and transformation of contaminants; The nutrient absorption by plants and; Pathogens naturally dying off and plants being eaten by them.

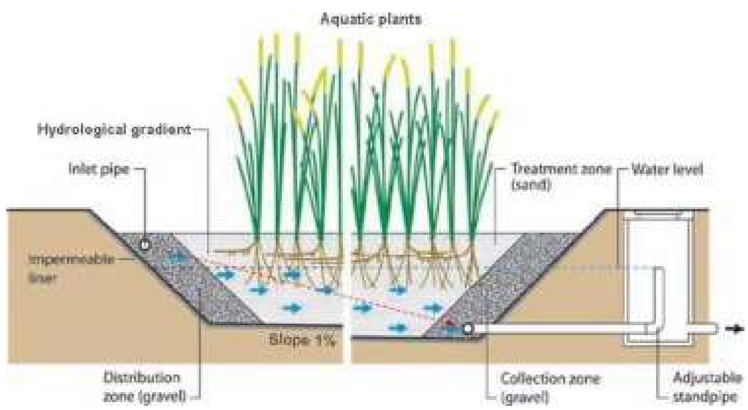

Figure 2.1 Constructed Wetlands (Wang et al., 2017)

The acknowledgement of the benefits that natural systems provide is one reason why wetland systems are gaining popularity. The increased interest in wetlands became evident due to the numerous benefits that wetlands and artificial wetlands can offer over traditional activated sludge or trickling filter systems. Wetlands frequently use less energy, are more dependable, need less upkeep, cost less and provide more ecosystem benefits (Vymazal, 2010).

Figure 2.1 gives a brief idea of how a constructed wetland looks like and the various components in it.

2.2 Characteristics

2.2.1 Substrates

Physically, wetland substrates are what hold up the wetland vegetation. They also give places for biochemical and chemical transformation processes and places to store waste and pollutants that have been removed from the environment. Substrates typically consist of various dirt, sand, gravel, and organic components (Yang et al., 2018). The majority of soils are suited for artificial wetlands (Lee and Scholz, 2005). However, different soil properties, such as cation exchange capacity (CEC), soil pH, electrical conductivity (EC), and soil of sand or gravel, should be taken into account for design considerations when choosing grounds to comprise when the receiving domestic and agricultural wastewaters are heavily loaded with nutrients, such as can be used to build with. According to a survey, soils with more than 15% clay are often ideal for use as wetland substrates (Vymazal, 2010). Additionally, gravel and sands are inexpensive materials that offer the perfect texture for hand planting and are very suitable for creating wetlands substrate. In addition, the substrate's organic content serves as a source of carbon to promote microbial activity. Additionally, consuming oxygen and organic material also forms anoxic environments, which are necessary for some treatment processes, according to Vymazal (2001); Scholz and Lee (2005).

2.2.2 Hydrologic Characteristics

The hydrologic regime of the wetlands contributes to the periods of inundation and saturation formed there. The status of the biota is influenced by hydrologic conditions, which also affect the properties and conditions of the soils and nutrients (Vymazal, 2001). According to Vymazal (2001); Scholz and Lee (2005), the flow and storage volume control how long water remains in a wetland and, consequently, the possibility of interactions between waterborne contaminants and the wetland environment. One of the most crucial components of wetlands is their hydrological properties, which include retention time, water depth, flow velocity across the wetland, and the number of days per year that the wetland is inundated (Al-Hadidi, 2021).

2.2.3 Wetland Vegetation

Due to the abundance of water, wetlands are often a suitable habitat for a range of microbial and plant species (Al-Hadidi, 2021). One of the most visible characteristics of wetlands is the presence of macrophytes, which sets artificial wetlands apart from natural soil filters or lagoons. Various plants, including emergent, floating, and submerged species, can be found in wetlands (Al-Hadidi, 2021). Emergent macrophytes are chosen for wetlands used for wastewater treatment because of the easy management of their occurrence and dispersion. Wetland vegetation's primary function is to absorb nutrients into plant biomass and oxygenate the soil around the plant roots (Al-Hadidi, 2021). In addition to immediately ingesting pollutants into their tissues, macrophytes also provide surfaces and an ideal environment for microorganisms to change nutrients and lower the concentrations of pollutants (Healy et al., 2007). In connection to the treatment procedure, the macrophytes that flourish in created wetlands have several characteristics (Table 2.1) that make them an integral part of the design.

Table 2.1 Role of Macrophytes in Constructed Wetlands treatment system (Al-Hadidi, 2021)

Macrophyte Property	Role in Treatment Process
Aerial Plant Tissue	Light attenuation → reduced growth of phytoplankton Influence of microclimate → insulation during winter Reduced wind velocity → reduced risk of re-suspension Aesthetic pleasing appearance of the system Storage of nutrients.
Plant tissue in water	Filtering effect → filter out large debris Reduced current velocity → increased rate of sedimentation, reduced risk of re-suspension Provides surface area for attached biofilms Excretion of photosynthetic oxygen → increases aerobic degradation Uptake of nutrients.
Roots and rhizomes in the sediment	Stabilizing the sediment surface → less erosion Prevent the medium from clogging in vertical flow systems Release of oxygen increase degradation (and nitrification) Uptake of nutrients

Release of antibiotics.

In artificial wetlands, persistent emergent plants, including bulrushes (Scirpus), spikerushes (Efeocharis), other sedges (Cyperus), rushes (Juncus), common reeds (Phragmites), and cattails (Typha) are most frequently employed (Table 2.2). Since plants for treatment wetlands must be able to tolerate the combination of constant flooding and exposure to wastewater containing relatively high and frequently varying concentrations of pollutants, not all wetland species are appropriate for wastewater treatment (Al-Hadidi, 2021). Wetland plants have evolved to withstand situations of extreme saturation (Al-Hadidi, 2021). Wetland plants, which typically take in oxygen through their roots, can also do so through their stems and leaves and then transfer it to their roots via specialised root cells (Al-Hadidi, 2021).

Table 2.2 Common plants used in constructed wetlands in grey water and wastewater treatment system (Al-Hadidi, 2021)

Species	Maximum water depth	Environmental condition
Arrow arum *Peltandra viginica*	30 cm	Fully sunny to partial cloudy conditions. Excessive wildlife value. Foliage and rootstocks are not eatable. Slow grower. Withstand pH: 5.0 – 6.5.
Arrowhead / duck potato *Saggitaria latifolia*	30 cm	Very aggressive colonizer. Mallards and muskrats can quickly consume tubers. More water loss through transpiration.
Common three-square bulrush *Scirpus pungens*	15 cm	Fast colonizer. Can tolerate periods of dryness. High metal removal. High waterfowl and songbird value.
Soft stem bulrush *Scirpus validus*	30 cm	Aggressive colonizer. Full sun. High pollutant removal. Provides food and cover for many species of birds. pH: 6.5 – 8.5.
Blue flag iris *Iris versicolor*	7-15 cm	Attractive flowers. Can tolerate partial shade but requires full sun to flower. Prefers acidic soil. Tolerant of high nutrient levels.

Broad – leaved cattail ** *Typha latifolia*	30-45 cm	Aggressive. Tubers eaten by muskrats and beaver. High pollutant treatment. pH: 3.0 – 8.5.
Narrow – leaved cattail ** *Typha angustifolio*	30 cm	Aggressive. Tubers eaten by muskrats and beaver. Tolerates brackish water. pH: 3.7 – 8.5.
Reed canary grass *Phalaris arundinocea*	15 cm	Grows on exposed areas and in shallow water. Good ground cover for berms.
Lizard's tail *Saururus cernuus*	15 cm	Rapid grower. Shade tolerant. Low wildlife value except for wood ducks.
Pickerelweed *Pontedaria cordata*	30 cm	Full sun to partial shade. Moderate wildlife value. Nectar for butterflies. pH: 6.0 – 8.0.
Common reed ** *Phragmites australis*	7 cm	Highly invasive; considered a pest species in many places. Poor wildlife value. pH: 3.7 – 8.0.
Soft rush *Juncus effuses*	7 cm	Tolerate wet or dry conditions. Food for birds. Often grows in tussocks or hummocks.
Spike rush *Eleocharis palustris*	7 cm	Tolerate partial shade.
Sedges *Carex spp.*	7 cm	Many wetlands and several upland species. High wildlife value for waterfowl and songbirds.
Spatterdock *Nuphar luteum*	150 cm 60 cm	Tolerant of fluctuating water levels. Moderate food values for wildlife, high cover value. Tolerate acidic water (up to pH 5.0).
Sweet flag *Acorus calamus*	7 cm	Produces distinctive flowers. Not a rapid colonizer. Tolerates acidic conditions. Tolerate of dry periods and partial shade. Low wildlife value.

Wild rice *Zizania aquattica*	30cm	Requires full sun. High wildlife value (seeds, plant parts, and rootstocks are food for birds). Eaten by muskrats. Annual, non-persistent. Does not reproduce vegetatively.

Because they are adapted to the local temperature, soils, and plant and animal communities and have an adequate treatment capacity, native and local species are advised to be utilised for wastewater treatment constructed wetlands (Vymazal, 2013). The performance of artificial wetlands is better in the presence of plants, according to several research comparing both types of treatment systems (Al-Hadidi, 2021; Kadlec and Wallace, 2008). Typically utilised in wetland treatment systems, significant nutrients (N, P, and K) make up 2.26, 0.25, and 2.6% dry weight of plant biomass, respectively. Depending on the vegetation type and climatic conditions, studies have shown that marsh vegetation can directly absorb and eliminate up to 20% of the nutrients in the treated effluent. Emergent macrophytes have an absorption capability of 50 to 150 kg P and 1000 to 25000 kg N per year (Al-Hadidi, 2021). However, plants' direct intake of nutrients only has a short-term impact on nutrient elimination Vymazal (2007).

2.2.4 Wetland Microorganisms and animals

Various microorganisms, such as bacteria, fungi, and algae, can be found in wetlands and are crucial for the transformation and removal of pollutants and the cycling of nutrients (Kadlec and Wallace, 2008). Wetland microorganisms can use organic matter to create gases and new cell tissue, eliminate soluble organic matter, coagulate and colloidal particles, and stabilise organic matter (Stottmeister et al., 2003). Aerobic and anaerobic microbial transformations occur in wetlands, and the microorganisms involved are the same as those used in conventional wastewater treatment techniques. Tolerances and requirements for dissolved oxygen, temperature ranges, and nutrients vary among different types of organisms, though. Constructed wetlands provide enhanced habitats for a variety of invertebrates and vertebrates. By breaking down waste, eating organic matter, and serving as significant mosquito larvae predators, invertebrate animals such as insects and worms play a unique role in the treatment process. They also attract a variety of amphibians, birds, turtles, and mammals, according to Kadlec and Wallace (2008).

2.3 Classification of Constructed Wetlands

CW systems are classified into different types based on the water flow direction, hydrology and plant species diversity (Stottmeister et. al., 2003; Herath and Vithanage, 2015) They can also be classified based on water flow characteristics as Free Water Surface (FWS) and Subsurface Flow (SF) CW systems. There are further divisions of SF-based CW systems as Horizontal subsurface flow (HSF) and vertical flow (VF) units. Plant species diversity can also divide the CW systems into three different categories named as: emergent macrophyte CW, submerged macrophyte CW and floating treatment wetland (FTW) systems. Among the types mentioned above CW systems rooted in emergent macrophytes are commonly used (Biswal and Balasubramania, 2022). When two or more different types of wetlands (e.g. Surface plus sub-surface flow systems) is referred to as hybrid/combined systems. There are also other classifications as saturated and unsaturated systems. Let's compare HSF and VF-based CW

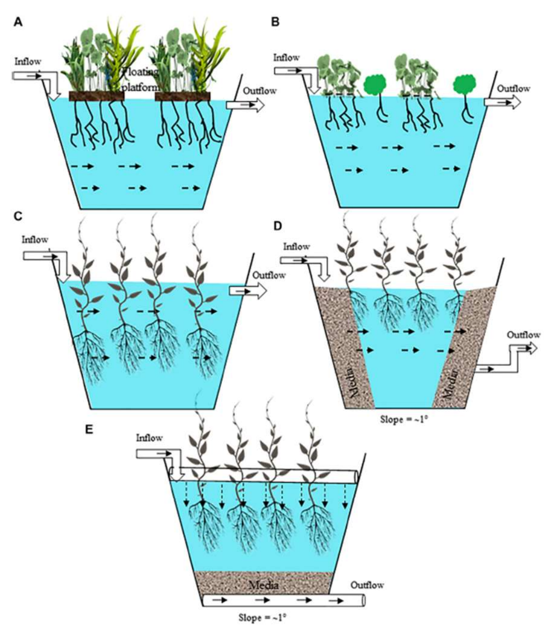

Figure 2.2 A schematic diagram of various constructed wetland (CW) systems. (A) Floating treatment wetland system, (B) Wetland with free-floating plants, (C) Horizontal surface flow/wetland with emergent plant system, (D) Horizontal subsurface flow wetland system, and (E) Vertical subsurface flow wetland system. (Biswal and Balasubramania, 2022)

systems. VF becomes more effective as intermittent vertical flow increases dissolved oxygen levels in the soil media, improving pollutant removal efficiency through aerobic biodegradation

(Biswal and Balasubramania, 2022). Among SF and FWS-based CW systems, the former type is primarily used in Europe and China as it requires less land and high efficiency is shown for removal of diverse pollutants (Wang P. et al., 2016), while the former type is mainly used in Australia and North America (Vymazal, 2011). While in Asia and Europe hybrid constructed wetlands mainly a combination of VF-HSF is used.

2.3.1 Surface Flow Wetlands

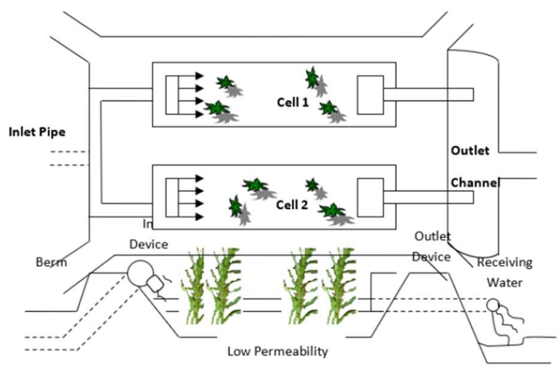

Figure 2.3 Plan and profile of a typical free water surface wetland (Al-Hadidi, 2021)

A shallow basin, soil, or other material to support plant roots, and a water control system that maintains a shallow depth of water are the components of a free water surface (FWS) wetland (Al-Hadidi, 2021). To maintain shallow water depth, low water flow velocity, and the presence of plant stalks and litter to control water flow, particularly in long and narrow channels, is necessary for FWS. When water is brought above the surface of the earth and flows through the wetlands at depths averaging less than 15 cm, ranging up to 30 cm, surface-flow constructed wetlands mimic natural wetlands (Figure 2.3) (Al-Hadidi, 2021). FWS wetlands can provide a perfect water treatment system, habitat for wildlife, and aesthetic benefits. In FWS wetlands, aerobic conditions are more prevalent close to the surface layer while anaerobic conditions are typically contained in deeper layers, waters, and substrate (Vymazal, 2011; Wallace and Kadlec, 2008; Vymazal, 2001). The proportional relationship of the concentration inflow has an impact on removal efficiency in many systems. While the effluent from the FWS-constructed wetlands had low levels of suspended particles and organics, which indicates improved treatment. Either seeding or transplanting can be used to establish wetlands plants. An FWS wetland can be easily and cheaply maintained by performing periodic burns of the treatment wetland's vegetation, monitoring and modifying water surface elevation, screening out debris from the wetlands' input and outflow structures, and removing sediment as needed (Bendoricchio et al., 2000).

Surface flow constructed wetlands can also classified into many other types of constructed wetlands, some of these can be observed in the following table.

Table 2.3 Types of surface flow constructed wetlands

Name	Figure	Description
CWs with Free-Floating Macrophytes	 **Figure 2.4** Surface flow constructed wetlands with Eichhornia crassipes (water hyacinth) in Langtou near Guangzhou, China (Vymazal, 2021)	Free-floating macrophytes are highly diverse in form and habitat, ranging from large plants, such as Eichhornia crassipes (water hyacinth, Figure 2.4) or Pistia stratiotes (water lettuce) with large leaves and roots, compared to very small plants, such as Lemnaceae (duckweeds e.g., Lemna spp., Sprodela polyrhiza or Wolffia spp.) with tiny roots. (Vymazal, 2021)
CW with Floating-Leaved Macrophytes	 **Figure 2.5** Constructed wetland (Ironbridge, Florida) planted with Nuphar lutea (spatterdock), designed for tertiary treatment of 800,000 PE in Orlando, Florida) (Vymazal, 2021).	Floating-leaved macrophytes (Figure 2.5) include plant species that are rooted in the substrate, and their leaves on long peduncles float on the water's surface. Typical examples of this type of macrophyte are water lilies (Nymphaea spp.), spatterdock (Nuphar lutea) or Indian lotus (Nelumbo nucifera) (Vymazal, 2021).

CW with Submerged Macrophytes	 **Figure 2.6** Surface flow CW with submerged macrophytes (mostly Myriophyllum spicatum, water milfoil) in Montréal, Canada) (Vymazal, 2021).	Submerged macrophytes root in the sediment and the entire plant is submerged in a water column. Submerged plants take up nutrients from the sediments. In some systems, naturally occurring species were used, such as in the case of the Florida Everglades Stormwater Area constructed wetlands, in which Najas guadalupensis (southern naiad) and Ceratophyllum demersum (coontail) are present (Vymazal, 2021).
CWs with Emergent Macrophytes	 **Figure 2.7** Surface flow CW with emergent plants (Eleocharis sphacelata, tall spikerush). Otorohanga, New Zealand (Vymazal, 2021).	A typical surface flow CW with emergent macrophytes (Figure 2.7) consists of a shallow basin or sequence of basins, containing 20–30 cm of rooting soil, with a water depth of 10–60 cm and a dense stand of macrophytes. The most common plants used in this type of CW are Phragmites australis (common reed), Typha spp. (cattails) and Scirpus/Schoenoplectus spp. (bulrushes) (Vymazal, 2013a).
CWs with Floating Mats of Emergent Macrophytes	 **Figure 2.8** Floating constructed wetland planted with Cyperus alternifolius. Ningbo, China (Vymazal, 2021).	Some emergent macrophytes are capable of forming floating mats, even though their individual plants are not capable of such an existence (Vymazal, 2021).

CWs with Trees	 **Figure 2.9** Dapeng Bay, Taiwan: surface flow constructed wetlands ePthloatnod Jawn iVthymmaaznagl. roves (Kandelia candel) for the treatment of mariculture wastewater (Vymazal, 2021).	The tree species that were used in constructed wetlands are Taxodium distichum (bald cypress) (Figure 2.4), Melaleuca quinquenervia (paper bark tea tree) or mangroves, which can be used to treat saline (waste)waters (Figure 2.9) (Vymazal, 2021).

2.3.2 Subsurface Flow Wetlands

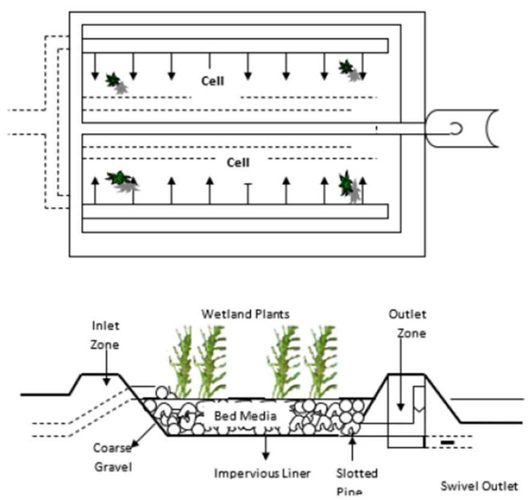

Figure 2.10 Plan and Cross-Sectional view of a subsurface flow wetland (Al-Hadidi, 2021)

Käthe Seidel created the first subsurface flow pilot-scale wetland in Germany in the 1950s (Vymazal, 2010). According to the direction of the water flow, constructed wetlands with sub-surface flow can be categorised as either horizontal HF or vertical VF (Kröpfelová and Vymazal, 2008). A sealed basin with a porous rock or gravel substrate, vegetation, and an outlet control mechanism make up a subsurface flow (SSF) wetland (Al-Hadidi, 2021). Up to 4-120

cm of gravel may be present in SSF wetlands, and the water surface level is maintained below the top of the gravel (Kadlec and Wallace, 2008). In SFF-constructed wetlands, the flow channel is horizontal, whereas in some systems, vertical flow paths have been observed (Figure 2.10) (Vymazal, 2010). Wetland seedlings must typically be planted in SSF because the gravel substrate is typically not ideal for seed germination and establishment (Kadlec and Wallace, 2008). Bacteria linked to the plant's underground organs (i.e., roots and rhizomes) and medium surface resembling trickling surfaces, as in the traditional biological treatment process, breakdown organic substances both aerobically and anaerobically (Scholz and Lee, 2005).
Subsurface flow constructed wetlands can also classified into many other types of constructed wetlands, some of these can be observed in the following table.

Table 2.4 Types of subsurface flow constructed wetlands

Name	Figure	Description
Horizontal Flow CW	 **Figure 2.11** Constructed wetland with a horizontal subsurface flow. Roseˇc, Czech Republic (Vymazal, 2021).	In HF CWs, mechanically pretreated wastewater slowly flows under the surface of the filtration bed filled with porous material planted with emergent macrophytes. During this passage through the filtration material, the wastewater comes into contact with a network of aerobic, anoxic and anaerobic zones. The aerobic zones are restricted to narrow zones adjacent to the roots and rhizomes that leak oxygen into the substrate (Vymazal, 2001). The filtration bed is sealed from the surrounding area by an impermeable layer; in most cases, a plastic liner to prevent leakage to the groundwater (Vymazal, 2021).
Vertical Flow CW		Vertical flow constructed wetlands generally consist of a bed of porous material, through which the water moves in a vertical direction. In general, this group of CWs incorporates various hydrologic

Figure 2.12 Wastewater distribution pipes at Changshu Advanced Materials Industrial Park VF CW, Suzhou, Jiangsu Province, PR China (Vymazal, 2021).

Figure 2.13 Down flow vertical constructed wetlands planted with Phragmites australis. Oberwindhag, Austria (Vymazal, 2021).

characteristics. There are three arrangements of vertical subsurface flow constructed wetlands: down flow, up flow and fill and drain. The most common type of vertical flow CWs is the free-drainage down flow unit, in which the outlet is open at the base of the filter bed. Wastewater is spread across the filter surface by a network of pipes (Figure 2.12) with multiple diffusers, to evenly distribute the wastewater to avoid short circuiting (Vymazal, 2021).

2.3.3 Hybrid Constructed Wetlands

When the treatment performance is to be improve, hybrid CWs which are an integrated system of multiple types of wetlands. HF CWs and VF CWs staged in series are the most frequent hybrid systems. These hybrid systems are the most efficient in treating total nitrogen than non-hybrid but the required space is also more along with an expensive build (Pandey, 2022)

2.3.4 Development Patterns

The following are two of the CW development patterns observed commonly (Pandey, 2022): Aerated CW and Tidal Flow. For wastewater treatment which are biological based, aeration is a typical and extremely valuable technical option. The artificial aeration system bubbles air from the bottom of the bed up through the saturated water column to the wetland's surface. On the basis of the bioactivity concept, aerated wetlands provide a improved treatment efficacy and hence good final effluent quality for diverse aerobically degradable pollutant removal (such as BOD, COD, and N) (Pandey, 2022). Tidal flow is a term which describes water movement. Tidal flow's goal can be described as increasing wetlands oxygen input and diffusion from the atmosphere, allowing CW to treat high-strength wastewater while also boosting nitrogen removal through nitrification which is a significant technical advancement. Quick filling and rapid draining are the heart of the tidal flow CW that is the intentionally generated tidal (Pandey, 2022).

2.4 Design Variations

Shapes and sizes of manmade wetland design variants are affected by site factors, allowing for the best possible construction, operation, and performance (Carty et al., 2008). Depending on the local soil characteristics and regulatory requirements, lined wetlands are generally installed to avoid infiltration (Kadlec and Wallace, 2008). Although there have been several studies and research papers about artificial wetlands, the best design for such wetlands has not yet been established because there are insufficient monitoring systems and insufficient running times to collect sufficient data for analysis (Moreira and Dias, 2020). Performance in monitored systems has varied, and it is difficult to estimate the effects of the many factors that influence performance, including location, wastewater characteristic or runoff, wetland design, climatic conditions, disturbance, and daily or seasonal changes (Kadlec and Wallace, 2008; Hammer, 2014; Al-Hadidi, 2021). In order to obtain good water quality during the treatment process, constructed wetland designs are most likely to closely resemble natural wetlands in every area of their structure. 2001's (Vymazal and Hammer, 2020). When creating constructed wetlands, the planning stage is crucial. Sites are frequently accessible, and a selection of native plant species can be made. A number of system types and configurations have been adopted to satisfy particular wastewater treatment demands. Additionally, each of the chosen sites is distinct, and each will have a different engineered wetland system (Hammer, 2020).

Four elements are needed to create a constructed wetland: a liner, distribution media (substrate), vegetation, and an underdrain system. The liner stops water leaks and prevents groundwater and the environment from being contaminated by wastewater. Polyvinyl chloride (PVC), one of the most widely used and dependable materials, is typically used to make the liner (Figure 2.14) (Al-Hadidi, 2021).

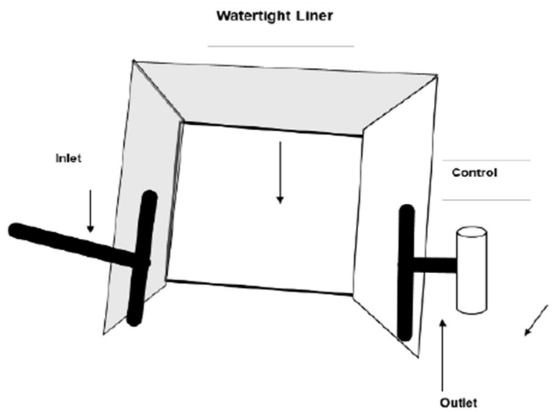

Figure 2.14 A Sectional View of Wetland Controls and Liner (Al-Hadidi, 2021)

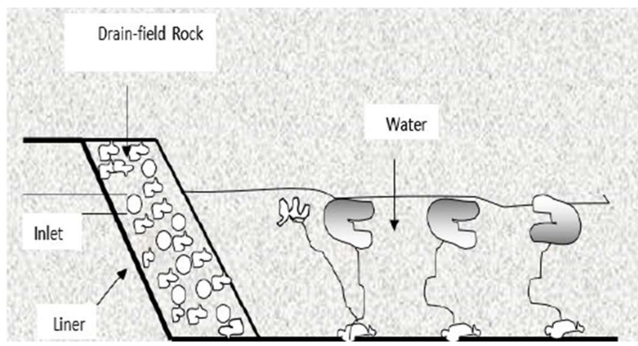

Figure 2.15 A Free Water Surface Flow Wetland Sketch (Al-Hadidi, 2021)

A distribution medium, often coarse rock measuring 2 to 5 cm in diameter, makes up the intake. The initial part of the distribution system distributes the influent wastewater over the wetland's width and cross section. Pea gravel media with a diameter of 1 cm to 2 cm is found inside the filter (Al-Hadidi, 2021). The depth of the pea gravel varies, although it often ranges from 45 to 60 cm. The wetland outlet's under-drain system is a slotted, 10 cm pipe that is covered in rock. In order to avoid direct contact with humans and stop mosquitoes from growing in the wetland, the under-drain transports the treated effluent out of the wetland and maintains the effluent level below the gravel surface (Al-Hadidi, 2021). Additionally, the water level is maintained at a level that supports plant growth. The most typical types of manmade wetland system design are shown in (Figures 2.15 and 2.16).

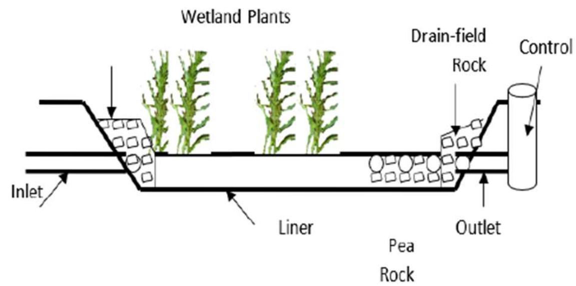

Figure 2.16 A Subsurface Flow Constructed Wetland Sketch (Vymazal, 2001)

The design criteria for both systems are different as can be shown in table 2.5

Table 2.5 Design criteria for Constructed Wetlands (LaFlamme, 2006)

Design parameter	Unit	Surface wetland	Subsurface wetland
Retention time	d	5 to 14	2 to 7
Water depth / media depth	M	0.1 to 0.8	0.3 to 0.6
Hydraulic loading rate	Mm d^{-1}	15 to 65	80 to 300
Volume flow rate	m^3d^{-1}	15 to 65	5 to 13000

Suggested design dimensions can be used for both wetland types as follows: (Al-Hadidi, 2021)
Surface Flow Wetland:
Surface area: (10 – 20) m². 60g-1.d-1.dof total BOD^5; Water depth: 10 – 50 cm; Hydraulic retention time: minimum 10 days; τ = L x W x D/Q (Volume of water m^3 and the Flow m³/d); Length/Width = minimum 4/1.
Subsurface Horizontal Flow Wetland: Surface area: 5 – 10 m² 60g-1. d-1of total BOD^5; Minimum Length is 6 m; max Length is 15 m; The slope of the reed bottom is (1%) from the top surface level; Depth of the inlet: ± 0.6 m; depth of the outlet: maximum depth 0.8 m; minimum depth 0.3 m.
Because it links all the functions and determines whether a created wetland succeeds or fails, hydrology is regarded as the most crucial design factor in constructed wetlands (Hammer, 2020). Abiotic wetlands components such as water and nutrient availability, aerobic or anaerobic soil conditions, water depth and velocity, and pH are all influenced by hydrology. Additionally, biotic factors such as water budget and gains from precipitation interference and losses from evapotranspiration by plants could be impacted by hydrology (LaFlamme, 2006; Hernandez and Mitsch, 2007).

The wetland experiences partial mixed flow rather than plug flow when water is moving through it (Al-Hadidi, 2021). Dead pools and little short-circuiting are required under plug-flow circumstances. A crucial design component that implies uniform flow behaviour is hydraulic retention time.

Flow characteristics through the wetland comprise (Davis, 1995):

Velocity is controlled by a sloping bed that maintains an adequate hydraulic gradient through the wetland to achieve the desired velocity.

Retention Time – is the time needed for a volume of water to travel from the inlet to the outlet of the wetland which is determined by the size, the depth, and the travel path through the wetland.

Depth of Flow – it must be determined to offer adequate storage and appropriate conditions for the wetland plants.

Travel Path – prevent short-circuiting through the system by providing an appropriate length to width ratio.

Water Balance –the sources and sinks that will occur in the wetland must be determined. Groundwater influences are negligible due to the usage of the liners. The precipitation and evapotranspiration contribution must be determined to show the effect on the wetland hydrology.

Hydrological considerations include climate and weather, hydro-period, hydraulic retention time, hydraulic loading rate, groundwater exchanges (infiltration and deep percolation), losses to the atmosphere (evapotranspiration), and overall water balance (Hammer, 2014; Hammer, 2020).

2.4.1 Hydrology

Hydrology or the water processes that occur in the wetland are important to the design and maintain the successful operation of the constructed wetlands (Al-Hadidi, 2021).

There are two main considerations: Water Balance and Retention Time. FWS wetlands are subjected to water loss due to evapotranspiration and seepage and subjected to gains (rainfall) which cause a fluctuating in water volumes and levels within the wetland. Retention time is the period of time that wastewater is retained inside the wetland is critical to the various treatment processes that occur. Required retention times vary depending on the concentration of the pollutants and the desired level and the target of the treatment. It was suggested that the best retention times for BOD removal are 2 to 5 days and it was recommended for BOD and SS removal between 7 to 10 days (Rowe and Abdel-Magid, 2020). Moreover, it was recommended 1 to 3 days for coliform removal, and 7 to 14 days for nitrogen removal while P removal is unpredictable at any retention time (Braskerud, 2002).

2.4.2 Water Balance

A constructed wetland's water balance is a record of all intake, storage, and outflow of water. Surface water (sewer or storm water), groundwater infiltration (in unlined wetlands), or rainfall make up the inflow. According to Davis (1995), Hammer (2020), Gorito et al. (2017), outflow consists of surface water evaporation, plant evapotranspiration, effluent discharge, and infiltration into groundwater. Rainfall can reduce effluent concentrations while evaporation loss can increase them. The constructed wetland water balance is crucial for assessing compliance with required constraints for the hydraulic loading rate, hydroperiod range, hydraulic retention time (HRT), and mass balances both during design and operation (Al-Hadidi, 2021).

The water balance equation for a constructed wetland can be expressed as:

$$\mathbf{S = Q + R + I - O - ET}$$

Where: S = net change in storage

Q = surface flow, including wastewater or storm-water inflow,

R = contribution from rainfall

I = net infiltration (infiltration less exfiltration)

O = surface outflow

ET= loss due to evapotranspiration.

Constructed wetlands are appropriate for tools for measuring water balance and ET due to having distinct inflow and outflow, and homogeneous substrate and vegetation (Drexler et al., 2004). Wetlands make up a large portion of the land use and ET is accounted for between 55-80% of water yield in some watersheds (Białowiec et al., 2014).

2.4.3 Hydraulic Retention Time (HRT)

Water treatment processes depend on the period that wastewater physically resides within the wetland boundaries (Almuktar et al., 2018). This period is known as retention time or could be defined in literature as hydraulic retention time or detention time. Retention time can be obtained from the following equation:

$\boldsymbol{t} = (\mathbf{n}_{\boldsymbol{y}} * \mathbf{d}A)/Q_{av}$

Where, t = average retention time (days) = (t_n) = nominal retention time

n_v = void ratio or porosity, corresponding to proportion of typical wetland cross section not occupied by vegetation. Typically, equal to 0.65 to 0.75

d = wetland water depth (m)

A = wetland surface area (m^2)

Q_{av} = average discharge (m^3/day) or equal to the average of Q_i and Q_o to water balance transit of the bed Davis (1995).

According to a survey, longer retention times speed up the elimination of more pollutants, while excessively extended retention times can be harmful (Kayombo et al., 2004). During typical high-water periods, it should be at least 3-5 days, according to the literature and empirical experiences. Additionally, others said that if the goal is to remove nitrogen, manmade wetlands with average retention durations of less than 2 days shouldn't be created (Koskiho et al., 2009). According to Scholz and Lee (2005), Al-Hadidi (2021), variations in water balance (such as altering influent discharges, rainfall, and evaporation conditions that combine to influence effluent discharges) affect retention time in practice. In actuality, t is the duration during which the wetland receives an identical amount of water flowing at a certain time (Wallace and Kadlec, 2008).

2.4.4 Hydraulic Loading Rate

Hydraulic loading measures the volumetric application of wastewater into the wetland. It is often used to compare wetland systems and indicates their potential to be overloaded by wastewater (Dong et al., 2011). The following equation can calculate the hydraulic loading rate.

HLR = Q/A

Where: HLR = hydraulic loading rate (m/day)

Q_i = influent wastewater flow (m^3/day)

In some cases, Q_{av} is used instead of Q_i,

A = wetland surface area (m^2) (Al-Hadidi, 2021)

The degree of interaction between wastewater and the manmade wetland system is greatly influenced by both HLR and HRT (Toet et al., 2005). For best treatment effectiveness in natural wetlands, HLR must be between 1 and 2 cm/day to prevent vegetative changes and improve treatment. nonetheless, Rowe and Abdel-Magid, 2020 found that hydraulic loading between 2.5 and 5 cm per day and 6 to 8 cm per day was ideal for FWS wetlands.

2.5 Limitations of Wetland processes

The light period, temperature, dissolved oxygen, and pH are examples of environmental elements that affect how quickly biochemical and biological processes occur. Short light intervals and cold temperatures have a negative impact on metabolic activities, which slow down the pace at which biota absorb pollutants. (Moreira and Dias, 2020; Kadlec and Wallace, 2008; LaFlamme, 2006; Hernandez and Mitsch, 2007; Jing et al., 2001). Low oxygen levels can disrupt the water column's aerobic respiration processes and lead to anaerobic conditions, according to (Arndt et al., 2013). Too high of a pH or too low of a pH affects metabolic activities, hence they are dependent (Kayombo, 2004). Due to the internal autotrophic processes of the wetland, outflow pollutant concentrations can occasionally be zero and, in other circumstances, can exceed inflow concentrations for certain parameters (Vymazal, 2007; Kröpfelová and Vymazal, 2009). The key forces influencing the existence and operations of a manmade wetland are hydraulics and hydrology. Hydraulics is concerned with the patterns and velocities of water movement within a manmade wetland, whereas hydrology describes the quantity and temporal distribution of the flow from a watershed into one (Braskerud, 2002).

The lack of standard information for engineers is currently limiting the design and construction of effective, low-cost systems. Constructed wetlands however have difficulties in treating complex pollutants. Land usage is also a significant difficulty considering constructed wetlands require more land than the conventional systems. Thus, making the construction of large systems impractical owing to high land costs and lack of suitable land. Small-scale systems' requirements can be stated as sites with flat, deep soils and a low groundwater table.

Chapter 3

Wastewater Treatment by Constructed Wetland Systems

3.1 Wastewater Treatment

3.1.1 Introduction

Wastewater flows from a septic tank through a pipe or other primary wastewater treatment system into the constructed wetland. There are two types based on the design and flow of wastewater it flows on top of the existing soil which is the surface or else through a porous medium such as gravel which is the subsurface. The distribution of flow is even across the width of the wetland cell. A waterproof liner is used on the bottom and sides of the cell so that leaks can be prevented and adequate water for the wetland plants is assured. The mentioned cell is planted with wetland plants like bulrushes and cattails. A dense mat is formed due to the roots and stems of the plants. Here wastewater is treated with the help of chemical, biological and physical processes. The water levels for constructed wetlands are controlled in both surface and subsurface systems. The average level for water is fixed at 1 inch below a gravel surface improving treatment and mosquito control in subsurface systems. A second cell may be added for more treatment. As the wastewater flows through the system, the suspended solids and trace metals settle and filter. Plants and organic materials also absorb trace metals. Organisms living in water, on rocks, in soil and on stems and roots of wetland plants use these organic materials and nutrients as food. Plants also provide oxygen which is majorly needed for organisms to live and grow. The rocks and soil are loosened by the plant roots so that water flow can occur quickly.

3.1.2 Water Quality Improvement

A wetland is a sophisticated and complicated ecosystem that includes elements including water, substrate, plants, plant litter, animals, and microbes (Al-Hadidi, 2021). Within treatment wetlands, numerous physical, chemical, and biological activities took place. The processes vary in their simplicity and complexity, which prevents us from fully understanding how they affect the course of treatment (Al-Hadidi, 2021). Typically, the treatment level, which needs to be extremely effective to meet discharge permit criteria, is the determining element in determining the limiting pollutant for which the wetland should be constructed Davis (1995). The capacity and percentage of mass removal of contaminants, which are dependent on the number of contaminants present in the wetland outflow, can be used to assess the treatment performance of wetlands. It is crucial that the chosen criteria accurately represent how well the wetland really performs in relation to the goals and intended applications of the wetland treatment system (Dotro et al., 2017).

The following elements of wastewater can be effectively removed by constructed wetlands: suspended particles, organic materials, excess nutrients, and pathogens' natural remnants (Vymazal et al., 2006). In terms of removing several contaminants, the SSF-constructed wetland surpasses the FWS wetland. SSF wetlands are highly effective in removing pollutants and fertilisers. The removal efficiencies of chemical oxygen demand (COD), total Kjeldahl nitrogen (TKN), total phosphorus (TP), total suspended solids (TSS), volatile suspended solids (VSS), and cadmium in both SSF wetland and FWS wetland were greater (Jindal and Samorkhom, 2005). According to Jindal and Samorkhom (2005), constructed wetlands are a recognised low-cost method for eliminating phosphorus from wastewater. A recognised low-cost method for eliminating phosphorus from wastewater is construction of wetlands (Almuktar, et al., 2018). Researchers have looked at using different materials as suitable substrates to improve the removal of phosphorus P using constructed wetland treatment systems.

Rarely are treatment wetlands' major goals to remove microbiological contamination from the wetlands (Vymazal and Health, 2005). However, wetlands are particularly good in eliminating pathogens; typically, the quantity of pathogens from wetland inflows is reduced by up to five times (Kayombo, 2004). Wetlands provide the ideal physical, chemical, and biological conditions for the eradication of harmful organisms. TSS removal and HRT are connected with the elimination of pathogens (indicators) in wetlands.

3.1.2.1 Suspended Solids Removal

Suspended solids of natural and surface flow constructed wetlands are typically near buoyancy, flocculent and easily disturbed. Higher velocities can dislodge adhering or deposited material, which forms the basis for the back-washing method of filter regeneration. Generation of particulate material can occur via all the mechanism, which occur in surface flow wetlands. Below-ground macrophyte parts – roots and rhizomes – die, decay and produce fine detrital fragments. Many other organisms are present in the bed that can contribute to TSS via the same route: algae, fungi and bacteria all die and contribute particulate matter to the water flowing in the pore space.

Non-settling/colloidal solids are removed by bacterial decomposition, adsorption to the wetlands media and plant root system (Vymazal, 2001). The extensive root system adds surface area to the wetland media, which reduces water velocity and reinforces settling and filtration in the root network.

3.1.2.2 Organic Compounds Removal

Treatment efficiency of the constructed wetlands for the removal of organics is generally high (Vymazal, 2001). Settleable organics are rapidly removed under quiescent conditions by deposition and filtration. Organic compounds are degraded biologically both aerobically as well as anaerobically by heterotrophs and autotrophs in the wetland systems which depends on the bed's oxygen concentration.

3.1.2.3 Phosphorous Removal

Orthophosphates such as PO_4^{-3}, HPO_4^{-2}, $H_2PO_4^-$, H_3PO_4 are available for uptake biologically in the constructed wetlands. The polyphosphates undergo hydrolysis in aqueous solutions and revert to the orthophosphate's forms. The hydrolysis is a very slow process. The organic phosphorous is an important constituent of industrial wastes and less important in most domestic wastewater. The average total phosphorous concentration in domestic raw wastewater is about 10 mg/L, whereas for the composition of TP- 30-50% comes from sanitary wstes while remaining from phosphate builders in detergents. For effluent in most cases the effluents standards range from 0.1 to 2.0 mg/L (Vymazal, 2001).

Phosphorous removal in wetlands takes place due to the following processes: retention by root bed media; plant uptake; storage in accumulating organic matter; accretions of wetlands soils; microbial immobilization; precipitation in the water column (Vymazal, 2001).

3.1.2.4 Nitrogen Removal

Nitrogen in wastewater exists commonly in the form of organic nitrogen, ammonia (NH_4^+-N), nitrite (NO_2^--N), nitrate (NO_3^--N) and gaseous nitrogen (N_2O-N and N_2). The organic nitrogen of the wastewater includes both soluble and particulate forms. The soluble organic nitrogen is mainly in the form of urea and amino acids (Vymazal, 2001). Typical domestic wastewater contains 20mg/L of organic nitrogen and 15 mg/L with the main sources from human excreta, kitchen litter and food processing wastes. The removal mechanisms for N in constructed wetlands are manifold and include volatilization, ammonification, nitrification/denitrification, plant uptake and matrix adsorption (Figure 3.1). Numerous studies have proven that the major removal mechanism in most of the CW is microbial nitrification/denitrification (Vymazal, 2001).

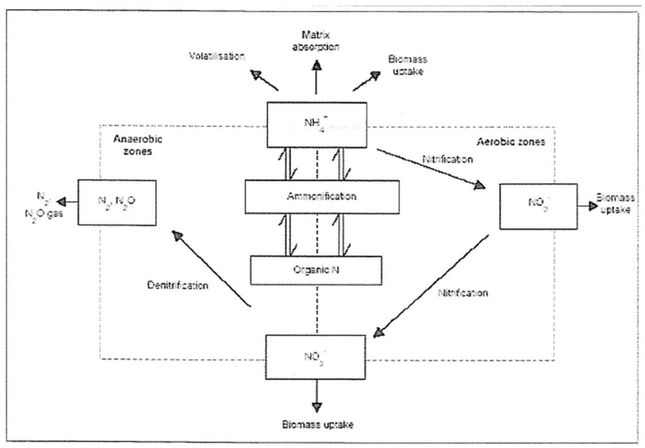

Figure 3.1 Nitrogen transformations in a constructed wetland treatment system (Vymazal, 2001)

3.1.3 Kinetics of CW

The treatment efficiency of the CW is normally expressed by the Mass Removal Rate (MRR), which represents the contaminants concentration difference in influent and effluent after subsequent stages of constructed wetland using the following formula:

MMR = $[(C_{in}Q_{in}) – (C_{out}Q_{out})]/A[g\ m^{-1}]$……… (1)

where A is the area of constructed wetland bed [m2], Q_{in} and Q_{out} are the average influent and effluent flow rates, respectively [$m^3\ d^{-1}$] and C_{in} and C_{out} are average influent and effluent contaminant concentrations, respectively in [$mg\ L^{-1}$] (Gajewska, 2020). A kinetic experiment is typically undertaken to account for the rate that differs from one contamination to another because the removal performance of any CW is a function of the contaminant decay rate. This in turn establishes the detention period that the specific CW's design should have in order to ensure full contaminant degradation at the intended rate. Normal assumptions and comparisons to other parameters make use of the first order decay rate (Gajewska, 2020). The CW design parameters include retention time, flow rates, surface bed area, contaminant concentrations and the decomposition constant coefficients (k) for wastewater treated in HF and VF beds and are normally obtained by applying the first order equation:

$(C_{out}/C_{in} = e^{-kT})$……… (2)

where k is the contaminant decay rate in d^{-1} and T is the hydraulic retention time in days.

One of the main drawbacks of the HCW is the limited data about their long-term efficiency (Vymazal, 2019). Vymazal, (2019), reviewed the treatment performance of around 114 HCWs including systems under operation for more than 20 years. The study indicated that HCW systems are very effective in treating organics and SS provided the proper loading rate. This efficiency increases with time, with a removal efficiency of up to 91% achieved after more than 20 years of operation (Vymazal, 2019).

3.2 Removal of Total Suspended Solids (TSS) and Chemical Pollutants

CW systems, also known as biofilters, are capable of removal of total suspended solids (TSS) and several chemical pollutants including chemical oxygen demand (COD), biochemical oxygen demand (BOD5), nutrients including total nitrogen (TN) and total phosphorus (TP), heavy metals and organics from wastewater (Hench et al., 2003; Zhang et al., 2014). In microcosm (VF) and mesocosm (HSF) based CW systems which are planted with emergent plants (eg Canna indica) and fed with saline wastewater, the removal of nitrogen and phosphorous was nearly 100% and under low and high influent loads was 94-100% (Liang et al., 2017). In a laboratory-scale VF-based CW system vegetated with Cyperus alternifolius (umbrella grass), the CW achieved 35–60% removal of TN and 77–80% removal of COD after 23 days of operation (Bilgin et al., 2014). Giácoman-Vallejos et al. (2015) investigated the performance of an HSF-based CW system for the treatment of domestic wastewaters and this system was more effective for decontamination of domestic wastewater with COD: 75% and TSS: 84% removal.

There was a recent study on wastewater treatment which used a hybrid constructed wetland that is a combination of multiple systems including floating treatment wetlands, HSF and VF CW. This combined unit shows high performance for removal of diverse pollutants including COD-77%, BOD_5- 84%, TN-93.8% and TP-94% (Dell'Osbel et al., 2020). A hybrid system consisting of VF and HSF CW system was fully capable of reduction of various pollutants from anaerobically digested blackwater, i.e. the above systems achieved 74% COD, 93% BOD_5, 50% TN and 61% TP reduction. Adding to the above data, the hybrid wetland showed high removal as high as 93% of antibiotics namely ciprofloxacin. There are single units specifically for the removal of TN but have showed lower treatment performance than hybrid CW systems. (Vymazal, 2013)

Table 3.1 Performance of various types of constructed wetlands (CW) for removal of TSS and diverse chemical pollutants from wastewater (Biswal and Balasubramanian, 2022).

Wastewater type	CW type	Pollutant removal efficiency (%)				
		TSS	BOD_5	COD	TN	TP
Domestic wastewater	HSFCW	87	95	90	-	-
Domestic wastewater	VSF	-	-	77 – 80	35 – 60	-
Domestic wastewater	SFHCW	84	-	75	-	-
Domestic wastewater	CW	87	89	93	70	72
Domestic wastewater	ICW	94	98	92	-	96
Domestic wastewater	HCW	-	93	74	50	61

3.3 Microbial Pollutants

3.3.1 Microbial Diversity in CW systems

The input of wastewater, substrate media, and the environment are the main sources of microorganisms into constructed wetlands (e.g., soil and atmosphere). In CW systems, the microorganisms in the substrate layer (such as the soil matrix) and/or the biofilm formed in the plant root zones are essential for the removal of pollutants (Despland et al., 2014; Lv et al., 2017). This means that optimal pollutant removal effectiveness during long-term operation could be provided by the presence of a stable and robust microbial community. For microbial characterization, understanding the richness, diversity, and composition of enriched microbial communities, as well as microbial activity and metabolic pathways in the CW systems, the majority of studies have used the 16S rRNA gene amplicon sequencing method (Arroyo et al., 2013; Sánchez, 2017). The CW microenvironments may be impacted by internal (such as pH, substrate media composition and depth, the presence or absence of vegetation, the quantity and quality of pollutants, and the availability of organic carbon) and external (such as ambient temperature and Sun light) factors, which could alter the microbial flora in CW ecosystems (Verduzo Garibay et al., 2021). Below is a quick summary of the dynamics of microbial communities that are enhanced in CW ecosystems that treat wastewater.

Depending on the type of wastewater (e.g., domestic, industrial, agricultural, poultry farm, etc.) to be treated in CW systems, the microbial diversity may differ. Proteobacteria, Bacteroidetes, Firmicutes, and Cyanobacteriachloroplast were the four primary phyla in the communities in SF-based CW systems treating swine waste. This indicates that Proteobacteria and Bacteroidetes accounted for the bulk of bacteria (more than 50%) in the CW system (Ibekwe et al., 2016).

Furthermore, statistical research shows that ammonia and phosphate have a considerable impact on microbial dynamics in wetland systems (e.g., Canonical correspondence analysis). Despland et al. (2014) discovered a difference between the diversity of microbial communities enriched in the soil (bottom) and Bauxsol pellet (top) layers in an unplanted CW, with the soil layer exhibiting the presence of ammonia oxidising bacteria and archaea. Bauxsol pellets, on the other hand, contained anammox, an aerobic ammonia oxidising bacterium, and denitrifying microbes.

These findings suggest that the CW microbiome's structure and functions may be influenced by the oxygen gradient profile in the substrate, which runs from the top (aerobic) to the bottom (anoxic/anerobic). The top layer of a long filter media with a 0.75 m depth showed the highest levels of microbial activity, such as fluorescence diacetate hydrolysis, according to Ruppelt et al. (2020). However, a somewhat shorter media filter (0.5 m deep) of VF-based CW systems showed reasonably consistent microbial activity. Additionally, Proteobacteria and Actinobacteria were the two predominant phyla of bacteria in the CW medium filter, while the abundance of the genus Flavobacterium columnare was higher in the long filter based on taxonomic classification at the genus level. A recent study that examined the microbial communities in various zones of an FWS CS system that treats wastewater found that Smithella, Ignavibacterium, and Methanothrix, three microbes that break down organic pollutants, are highly abundant in phytofilters, while Parcubacteria, Proteiniclasticum, and Macellibacteroides are scarce in the sedimentation tank (Semenov et al., 2020).

Table. 3.2 Microbial diversity enriched in constructed wetlands (CW) under various climatic conditions/regions (Biswal and Balasubramanian, 2022).

Wastewater Type	CW type	Climate condition/study region	Microbial diversity
Domestic Wastewater	SF CW	Summer season	Phyla namely Proteobacteria, Actinobacteria and Bacteroidetes
Domestic Wastewater	SF CW	Winter season	Phyla namely Proteobacteria, Bacteroidetes, Cyanobacteria and Unclassified
Tourism house wastewater	HSF CW	Cold/winter season	Genera namely Glomus sp., Rhizophagus sp. and Acaulospora sp. (Fungi)
Urban Wastewater	VSF CW	Mediterranean climate	Nitrosospira (AOB), Nitrososphaeraceae (AOA) and Nitrobacter (NOB)

The quantity of microbial communities in CW systems may be influenced by the planted plants as well. Generally speaking, vegetation increases the biofilm's metabolic richness and microbial activity (Lv et al., 2017). According to Wang et al. (2016), two phyla—Proteobacteria (51%) and Bacteroidetes (34%)—accounted for the whole bacterial population in a CW planted with Iris pseudocorus, while Proteobacteria (72%) and Bacteroidetes (23%) were the predominate bacteria in a CW planted with Typha orientalis Presl (Wang P. et al., 2016a). Additionally, the I. pseudacorus CWsystem had a higher concentration of nitrifying bacteria (such as Nitrosomonas, Nitrosospira, and Nitrospira) than the T. orientalis Presl vegetated CWsystem did. Arroyo et al. (2013) observed that Proteobacteria was the dominant phylum among the enriched microbes in mesocosm-scale CW systems treating metal-rich (As and Zn) wastewater. Additionally, phylogenetic analysis revealed that of the three design factors (i.e., vegetation, flow, and substrates), vegetation and water flow features have the most impact on the structure and makeup of the microbial communities. Overall, different microbial communities, including nitrifiers, denitrifiers, and organic degraders, are found in CW systems treating wastewater based on the characteristics of the effluent.

3.3.2 Removal of Microbial Pollutants

Wastewater frequently detects microbial contaminants like faecal coliforms, enterococci, coliphage and pathogens which pose a detrimental effect on public health (Naidoo and Olaniran, 2014). There have been many studies that examined the effectiveness of CW systems which were focused on removal of both faecal indicator organisms and pathogens. It was observed that for an HSF wastewater wetland system which was planted with Typha domingensis, the faecal coliform reduction was one order of magnitude, which explains the concentration of faecal coliform in influent and effluent to be 1.5×10^3 and 6.0×10^2, respectively (Schierano et al., 2020). But there were no consequential results on the studies regarding the removal of Escherichia coli and Pseudomona aeruginosa as both these bacteria can be detected in multiple effluent samples collected at various time intervals (Biswal and Balasubramanian, 2022). A recent study was done on an integrated system which contained HSF-VF CW systems were fed with wastewater from a local wastewater treatment plant, the system in study was able to reduce efficiently the concentration of pathogenic bacteria which also included E.coli and total coliforms which when calculated can be said to be at 99% or ~4.5 $\log_{10}$ units (Vega De Lille et al., 2021). Another study evaluated the performance of a hybrid system with a combination of VF and HSF for removal of pathogens in an environment of tropic type climate, with the results of removal reaching a high rate of removal of 3 log units for E. coli, 4 log units for total coliform and 90% for helminth eggs (Garcia et al., 2013). Faecal coliforms and Salmonella typhimurium in water had a die-off rates of 0.256 and 0.345 respectively, while in sediments the die-off rates were predicted as 0.151 and 0.312 respectively (Biswal and Balasubramanian, 2022).

Table 3.3 Performance of various types of constructed wetlands (CW) for removal of diverse microbial pollutants from wastewater. The detailed information is provided in supplementary material (Biswal and Balasubramanian, 2022).

Wastewater type	CW type	Microbial pollutant removal efficiency (% or log removal)			
		Faecal coliform	Total coliform	Escherichia coli	Enterococcus
Municipal wastewater	SFCW	>99.97	-	-	-
Municipal wastewater	HFCW	-	4 log	-	-
Urban wastewater	HSFCW	-	1.1 - 1.4 log	1.1 - 1.3 log	1.8 - 2 log
Secondary wastewater	SFCW	0.256 $\log_{10}$ d^{-1}	-	-	-
Domestic/swine wastewater	SFHCW	86 – 91	80 – 82	-	-
Swine wastewater	SFCW	98	-	99	-
Municipal wastewater	HSFCW-MP	1.13 log	-	-	-
Wastewater	CW	-	-	6.7	84
Municipal Wastewater	SFCW	87.9 – 92	-	97.5 – 99.8	99.98 – 99.9

Note: SFCW: Surface flow constructed wetlands; HFCW: Horizontal flow constructed wetlands; HSFCW: Horizontal subsurface flow constructed wetlands; SFHCW: Subsurface flow horizontal constructed wetlands; HSFCW-MP: Horizontal subsurface flow system (HSFCW) combined with a maturation pond (MP).

In addition to the above data, for coliphage and Giardia in water the die-off rates in $\log_{10}$ per day were 0.397 and 0.029 respectively whereas the die-off rates in sediments they were 0.107

and 0.37 respectively (Alufasi et al., 2017). In HSF-based CW systems with a vegetation of two macrophytes named as Typha dominguensis and Typha latifolia, the removal efficiencies for the faecal coliform and total coliform from domestic wastewater were 86-91% (Giacoman-Vallejos et al., 2015).

There was a recent study done on hybrid systems which was a HSF-based CW with a maturation pond was revealed to post a result that the removal of faecal bacteria which included faecal coliform (FC) and faecal streptococci (FS) from the municipal secondary wastewater varied between 1.13 and 0.59 had a variation between 1.13 and 0.59 log units respectively (Ergaieg and Miled, 2021). A study was involved wherein two types of microbiological methods for quantification was applied to remove faecal indicator bacteria from wastewater in CW systems and the wetlands achieved a 50% reduction of E. coli based on the evaluation by a culture-based technique (Lamori et al., 2019). But a quantitative polymerase chain reaction which was a q-PCR based analysis showed only 6.7% reduction of E. coli. In addition to this the concentration of Enterococcus and Human-associated Bacterioidales (HF183) was decreased by 84 and 67% respectively (Biswal and Balasubramanian, 2022). The following table summarises the removal of microbial pollutants by the CW systems. We can deduct from the observation of the table that the removal of microbial pollutants from different systems was different depending on different criteria.

3.4 Factors Impacting Pollutant Removal Efficiency

The interaction that take place between abiotic and biotic components and also the external factors has the ability to influence the treatment efficiency of CW systems. Pollutant removal performance of CW systems gets influenced by many parameters including CW physical configurations, hydraulics, substrates, plant species diversity, dissolved oxygen (DO) level, climatic conditions (e.g. temperature/season) etc. (Biswal and Balasubramanian, 2022; Zhu et al., 2014; Herrera-Cardenas et al., 2016). The efficiency of pollutant removal varies with a change of CW system configurations (Chen et al., 2016). The same study had made comparisons on the performance of antibiotics removal of three different CW configurations which were SF and SSF (VF and HSF CW) wetland facilities. There was also SSF systems (89.1–98.9%) showing higher performance in removing the antibiotics than the SF systems (76%) like erythromycin. In addition to that, comparing HSF and VF configurations, HSF

(98.9%) had higher capability for the removal of pollutants compared to the VF units (89.1%). In another study there were differences that were observed in the reduction of pollutants in pilot scale HSF-based and VF-based CW systems. The former type showed high performance which involved removal of COD with 74% and ammonia with 79% as the removal amount while the latter with a removal percentage of 64% was effective mainly for nitrogen (Xu et al., 2016).

There are many factors affecting the performance of the CW systems and HLR standing for Hydraulic loading rate is one of them and in the most cases that were observed the pollutant removal efficiency was observed to be decreasing with an increase in the HLR (Trang et al., 2010). Analysing a pilot-scale HSF CW system the efficiency for removing COD, TP and TN was 95% for all when the HLR was 0.025 m/day, but when the HLR was doubled (0.5 m/day) the same efficiency was decreased to levels of 91, 87, and 89% (Angassa et al., 2019).

Hydraulic retention time can be considered as an important parameter which has an impact on the effectiveness on the CW systems. The removal of COD from cheese whey wastewater was studied by Sultana et al. (2016) in pilot-scale unplanted and planted (reed: Phragmites australis) HSF-based CW systems at four different HRTs (1, 2, 4 and 8 days). In both CW systems, the amount of COD removed saw a drop in proportion to a decrease in HRT; for example, whereas in an unplanted CW system, the amount of COD removed got decreased from 100 to 76% when HRT was cut from 8 days to 1 day.

However, a comparable decline in performance was also observed in the vegetated cell (a drop from 100 to 76% with a reduction in HRT from 8 to 1 day). Sarmento et al. (2013) examined the effects of four different HRTs—1, 2, 3, and 4 days—on the removal of various contaminants from swine wastewater in VF-based CW systems. The effectiveness of pollutant removal was seen to increase as HRT increased up to 3 days before declining. In a recent pilot-scale study, Typha latifolia and Phragmites australis were used to treat synthetic wastewater using a vertical subsurface flow CW. As the HRT increased from 2 days (69.4%), 4 days (77.6%), 6 days (86.3%), 8 days (86.4%), and 10 days (88.8%), the efficacy of pollutant removal (e.g., COD) increased steadily (Shruthi and Shivashankara, 2021b).

Using a horizontal subsurface flow, the same research team has produced another study. The COD removal rate increased by 65.0, 74.4, 82.8, 86.1, and 88.3% with increases in HRT of 2, 4, 6, 8, and 10 days, respectively, according to CW ran under similar operational settings (e.g., HRT) (Shruthi and Shivashankara, 2021a). The effectiveness of pollutant removal was marginally higher at HRT of 1.5 days (COD: 65.02%, ammonia: 4.9%, and phosphate: 11.1%) than at HRT of 2.5 days (COD: 55.5%, ammonia: 4%, and phosphate: 11%) in a study by Badhe et al. (2014) on the performance of a free surface, up-flow CW planted with Typha latifolia. In a surface flow CW, operating the system at a longer HRT had a positive impact on the reduction of the microbial pollutant concentration; for example, 91% of the E. coli was removed at a HRT of 11.6 days, but the removal efficiency fell to 66% when the system was operated at a shorter HRT of 0.9 days (Diaz et al., 2010).

One of the key elements in CW systems, plants have the potential to affect how well wetlands remove contaminants. Sarmento et al. (2013) compared the efficacy of three plant species—Cyperus sp. (grass), Heliconia rostrata (shrub), and Hedychium coronarium (herbaceous)—in removing different pollutants from swine wastewater in VF-based CW systems and discovered that Cyperus sp. was most effective (COD: 69%, TKN: 57%, NH4 +: 62%, and In addition to plant species diversity, plant root characteristics (length, biomass, architecture, etc.) may also affect the rate of pollutant uptake because among the three plant species, Canna (a flowering plant), Phragmites australis (a reed), and Cyprus papyrus (a flowering seed plant), which were all grown in VF-based CW systems studied for the decontamination of municipal wastewater, the uptake of nitrogen and phosphorus as well as the removal of fe (Abou-Elela and Hellal, 2012). Canna performed well because the roots were evenly and widely distributed over the CW filter bed. In contrast to phosphorus removal, the diversity of vegetation species in CW had a greater impact on nitrogen removal (Liang et al., 2017). Table 7 lists the variety of plant species cultivated in various CW systems run under various climatic circumstances (warm, cold, tropical, dry, semi-arid, etc.).

The filter media composition has a big impact on how well CW systems remove pollutants. It is vital to select substrates with high ecological activity and high adsorption capacity in CW systems to achieve high performance (Chen et al., 2009). According to a recent study on tidal flow CW systems (planted with Phragmites or Vetiver), organic-based media (biochar, coco-peat, and coal) performed better at removing pollutants than waste (slag)/construction-based media (gravel and concrete block), which had lower removal performance (N: 49–69% and organics: 74–95%). Slag and construction media outperformed the rest of these materials in terms of removing phosphorus (by about 93%) (Saeed et al., 2020). Li et al. (2019) demonstrated that the addition of biochar to SF CW systems boosted the nitrogen removal efficiency; specifically, the nitrate removal increased by 5% with the addition of 10% (V/V) biochar and by 10% with the addition of 20% (V/V) biochar (Biswal and Balasubramanian, 2022).

The carbon/nitrogen (C/N) ratio affects the elimination of nitrogen and COD. When the C/N ratio in HSF-based CW systems increased, Zhu et al. (2014) saw an increase in the removal of TN, nitrate, and COD from wastewater; the C/N ratio of five showed good removal performance. The rise in the C/N ratio, which was brought on by the drop in dissolved oxygen levels brought on by the biodegradation of organic components, had the opposite effect on the elimination of ammonia (Zhu et al., 2014).

Li et al. (2014) found that greater C/N ratios (like 14.3) increased the rate of denitrification. High DO concentration is advantageous for nitrification and organic degradation because Li et al. (2014) found that COD and TN removal in horizontal subsurface flow CW (HSFCW) systems increased from 87.2 to 55%-90.9 and 88.1%, respectively, with increases in DO concentration from 1.3 mg/L to 3.4 mg/L.

Since a recent study showed that the plantation of Vallisneria natans gave the necessary oxygen to the CW system and higher nitrogen removal (90% NH_4^+-N) was achieved, cultivation of a suitable plant can also offer enough oxygen to CW systems (Fu et al., 2021).

In a study (Herrera-Cárdenas et al., 2016), the effects of three different parameters were compared, including HRTs (1, 3 and 5 days), substrate types (river gravel, fine and coarse volcanic gravel), plant types (Cyperus papyrus, Phragmites australis, and Thypa latiffolia), and organic loads from effluent from a wastewater treatment plant. According to this study's findings (Herrera-Cárdenas et al., 2016), HRT is the main factor that has a substantial impact on the treatment process in HSF CW systems. While the removal of organics ranged from 70 to 75%, that of micropollutants ranged from 55 to 99%. Furthermore, the BOD_5 elimination was about 75% at 1 day of HRT, but it was increased to almost 90% at 3 or 5 days of HRT.

Seasonal changes have an impact on how well CW systems remove pollutants. For instance, CW systems were highly successful for the removal of TN, TP, and particulate phosphate in spring and summer but less effective in autumn and winter, according to Wang et al. (2021) (Wang et al., 2021a). Dong et al. (2011) noted a seasonal variation in the efficacy of an integrated CW system's pollutant removal. For instance, 98% of TN and TP were removed from wastewater in the summer. However, throughout the winter, the removal efficiency dropped to 96% for each. The drop-in microbial activity and diffusion rates may be the cause of the performance decline at lower temperatures (Dong et al., 2011).

One of the crucial processes for removing contaminants from wastewater in CW systems is microbial degradation. Thus, in addition to CW operational parameters and the local climate, the diversity and richness of different functional microbial communities (nitrifiers, denitrifiers, organic carbon degraders, etc.) may have an impact on how well CW systems treat waste water. Notably, CW design configurations and vegetation are two important elements that affect the enrichment of functional microorganisms (Zhang et al., 2018).

High microbial activity and metabolic richness are displayed in CW systems with saturated and aerated designs (Zhang et al., 2018). According to Zhou et al. (2020), intermittent aeration in a subsurface flow CW boosted microbial abundance while reducing microbial diversity. Iris pseudacorus and Typha orientalis Presl were the two different plants that Wang et al. (2016) evaluated for their impact on the microbial communities in a subsurface flow CW. They found that vegetation positively influences bacterial richness and diversity, and that the abundance of nitrifying bacteria (Nitrosomonas, Nitrosospira, and Nitrospira) was higher in CW systems planted with Iris pseu. The performance of CW systems for the removal of pollutants from wastewater is positively influenced by planted subsurface flow/hybrid configurations, aerobic environment (high DO levels), with operations at low HLR, high HRT, and relatively high environmental temperature (e.g., summer season).

Table 3.4 Diversity of plant species used in constructed wetlands (CW) under various climatic conditions/regions (Biswal and Balasubramanian, 2022).

Wastewater Types	CW Type	Climate condition/study region	Plant Species
University Dormitory wastewater	HC W1	Arid and warm climate	Arundo donax, Cortaderia selloana, and Phragmites australis
Synthetic/secondary treated wastewater	HSSF CW	Arid climate	Bassia indica (halophyte
Sewage	SSF CW	Moroccan climate	Phragmites australis and Arundo donax
Greywater	HCW2	Tropical climate	Heliconia psittacorum, Cyperus isocladus, Canna sp., Arundina bambusifolia and Alpinia purpurata
Greywater	HCW3	Semi-arid climate temperate climate	Typha latifolia (common cattails)

Municipal Wastewater	SSFCW	Semi-arid climate	Phragmites australis (hydrophytes)
Petroleum industry wastewater	VFCW	Hot arid climate	Phragmites australis and Typha latifolia
Synthetic wastewater	HCW4	Low temperature	Canna indica L. and Phragmites australis (Cav.) Trin. Ex Steud (common reed)
Fish Farm effluent	HSSFCW	Cold climate	Phragmites australis (Cav.) Trin. ex Steud. (common reed) and Typha angustifolia L. (narrowleaf cattail)
Domestic wastewater	SSFCW	Cold climate	Phragmites australis (common reed)
Sewage	SMCW	Cold climate	Bryum muehlenbeckii (moss)
Dairy wastewater	Field-scale CW	Cold climate	Typha latifolia and Phragmites australis
Urban Wastewater	HCW5	Warm climate	Phragmites australis (common reed)

3.5 Circular Economy Approach

Using onsite constructed wetlands promotes sustainable water management in many ways. Having the wastewater treatment system onsite more easily allows water to be reused multiple times and for multiple purposes. Water can be reused for cooling towers, toilets, irrigation, habitat creation, percolation back into an aquifer, ornamental water features, and some crops and industrial uses.

These systems further increase sustainability by reducing energy use, and eliminating the infrastructure and its associated environmental impacts, required when pumping wastewater to a centralized plant. Additionally, constructed wetlands can be more cost effective, due to their lower energy and infrastructure requirements and can also reduce demand on existing centralized treatment plants, thereby preventing costly upgrades.

Furthermore, onsite treatment systems can be incorporated into the design of buildings and landscaping, resulting in the reduction of use of other materials and resources. Also, by having the system incorporated into their surroundings, building occupants interact daily with the components of the treatment system, thereby promoting increased education and awareness of water resource issues.

Based on the quality of effluents that was produced from the constructed wetlands, the water that is reclaimed can be reused for various purposes like support of recreational activities mainly swimming pools, sports, events, also for agricultural purposes like crop production, augmentation of freshwater – rivers, lakes, ponds and groundwater as in aquifer recharge (Tao et al., 2017; Almuktar et al., 2018). There have been several studies on the effluent quality that suggests that constructed wetlands have effluent of the local water quality standards for recreational/agricultural reuse or discharge into surface waters (Al-Wahaibi et al., 2021; Díaz et al., 2010; Trang et al., 2010). According to Dáz et al. (2010), the majority of the time (almost 93% of the sampling time) the concentration of E. coli in the effluent of surface flow wetlands was below the USEPA limit for recreational water. (i.e., 126 CFU/100 ml), while enterococci levels were under the only 30% of the sample time was spent with the standard (33 CFU/100 ml). A new research on a large-scale vertical flow CW mentioned this with step-feeding of outside carbon, the level of nitrate in the Oman's irrigation standard for wastewater was not met (11.3 mg NO_3-N/L) (Al-Wahaibi et al., 2021). in horizontal pilot scale underground flow CW systems that treat domestic wastewater, Most people reportedly get what they need from wetlands' cleaned wastewater of the national standards of Vietnam (except ammonia and TN) when treating effluent is discharged into surface waterways (Trang et al., 2010). The treatment efficiency of CW was found to be greater when it was operated at low water height (10 cm) in a second pilot-scale investigation on a multistage horizontal subsurface flow CW fed with raw urban wastewater and operated at two different water heights (10 vs. 40 cm) (Herrera-Melián et al., 2020). According to the Spanish National Regulation for the discharge of treated effluent into the environment and the potential reuse of treated effluent for various purposes, the treated effluent (such as COD, TSS, turbidity, and E. coli concentration) demonstrated a high degree of compliance (Herrera-Melián et al., 2020). The effects of different filter media, including mafenide, steel slag, bamboo charcoal, and limestone, were examined by Lu et al. (2016) in a vertical upward-flow subsurface-flow CW for the treatment of sewage from rural households.

Mianite stone outperformed the other four media materials in terms of pollutant removal, and the treated effluent complied with Chinese discharge standards (GB18918-2002). The concentration of faecal coliforms and total bacteria in the CW effluent were below the Chinese National Standard for release of treated effluent from municipal wastewater treatment plant, according to another investigation on a combined system made up of ponds and a surface flow constructed wetland (Wang et al., 2005).

As there are many advantages there are also many barriers to this. Although these systems are efficient and cost effective, there are limitations and barriers to their implementation. Wastewater treatment is a regulated process, governed by many entities. Permitting of constructed wetlands may pose difficulties, especially with agencies unfamiliar with these types of systems.

Constructed wetlands require monitoring and maintenance, they are not construct and forget systems. Building owners must have staff dedicated to their upkeep, including an educational component regarding use of appropriate chemicals.

Constructed wetlands require a considerable amount of land or space, which may make them difficult to extensively implement in dense urban areas. Additionally, this space requirement may make them more difficult to apply at the scale (millions of gpd) of large centralized treatment plants.

Chapter 4

Summary and Future Plan of Work

4.1 Summary

Compared to many other wastewater treatment technologies, CW systems have been shown to be cost-effective, environmentally friendly, and sustainable since they are built to replicate natural treatment processes in a controlled environment of minimal or no energy use. Research and business sectors continue to perceive CW as one of the most effective methods for treating wastewater, especially when it comes to the smallest of towns. The wetland system, like many other technologies, has not yet been fully developed. face a variety of difficulties, such as media choice. CW medium not only promotes biofilm for plant development, but it is also anticipated to offer strong adhesion and attachment places where biofilm can build.

Due to CW's extremely low power usage compared to conventional treatment technologies, there has been an evolving trend in its implementation as a promising eco-friendly and affordable wastewater treatment solution. CW showed to be a successful treatment strategy, especially for BOD5, TN, TSS, and TP, with removal efficiencies ranging from 70 to 83% generally. There are two primary CW configurations: HCW and VCW. Each has unique benefits and constraints, such as the availability of land and the quality of the original wastewater. The hybrid CW system is a developing configuration that combines the benefits of both systems and can offer an aerobic as well as anaerobic environment that is suitable for a larger range of pollutants, despite the limitations that each configuration faces.

Subsurface (horizontal and vertical) flow/hybrid systems are among the CW layouts that are efficient at removing chemical and microbiological pollutants from wastewater. Non-potable water can be made from the reclaimed water. Pollutant removal in CW systems is primarily facilitated by physical-chemical processes (sedimentation, adsorption, precipitation), microbiological activities (biodegradation, assimilation, nitrification, and denitrification), as well as plant-mediated processes (phytoremediation and assimilation). Nitrifying bacteria, denitrifying bacteria, and microorganisms that break down organic debris make up the important microbial flora that is enriched in CW habitats. Additionally, two phyla—Proteobacteria and Bacteroidetes—dominate the CW microbiome in a dominant manner. The efficiency of CW systems to remove pollutants is accelerated by key operational and environmental factors such low HLR, high HRT, high dissolved oxygen concentrations, and operating throughout the summer. Numerous kinetics, hydrologic, and mechanistic-based models have been produced in addition to experimental efforts for the prediction of the operation and performance of CW systems.

However, in addition to the high treatment efficiency, the constructed treatment wetlands have recently been shown to have a great potential in the new sustainable and circular economy in the urban environment. Constructed wetlands can effectively treat, accumulate and recycle water and nutrients for further use (Vymazal, 2021)

This gives a direction to move forward to in regards to the water reuse after treatment of domestic wastewater. The recent studies have been regarding reviews for constructed wetlands and its treatments systems. Today, when resources are produced less than what they are consumed, there is a need to revaluate our methodologies in wastewater treatment and utilise circular economy approach. Circular economy is defined as a cycle wherein recycling of the produced parameters are done.

4.2 Future Plan of Work

Table 4.1 displays the future direction of the work according to the tasks defined with the help of objectives.

Table 4.1 Future plan of work

Tasks	Aug ‘22	Sept ‘22	Oct ‘22	Nov ‘22	Dec ‘22	Jan ‘23	Feb ‘23	Mar ‘23	Apr ‘23	May ‘23
Study various types of eco-centric domestic wastewater system										
Study Constructed Wetlands and its different characteristics										
Study different types of constructed wetlands and the treatment systems										
Domestic Wastewater treatment and its reuse potential										
Sampling Analysis for assessing substrate and micro-organisms requirements for constructed wetlands										
Design and optimisation conditions for hydrology										
Investigate the effluent standards and comparison with different standards of water quality usability										
Development of inputs for investigating circular economy approach using the effluent treated water from the CWs for household purposes										

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