ISTANBUL TECHNICAL UNIVERSITY ★ GRADUATE SCHOOL

INVESTIGATION OF GREY WATER TREATMENT PERFORMANCE IN A VERTICAL SUBSURFACE FLOW CONSTRUCTED WETLAND

M.Sc. THESIS

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Department of Environmental Engineering

Environmental Biotechnology Programme

Thesis Advisor: Assoc. Prof. Mahmut Ekrem Karpuzcu

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DİKEY AKIŞLI BİR YAPAY SULAK ALANDA GRİ SU ARITMA PERFORMANSININ DEĞERLENDİRİLMESİ

YÜKSEK LİSANS TEZİ

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Ömer Furkan Kılıç, a M.Sc. student of ITU Graduate School, student ID 501191808, successfully defended the thesis entitled "INVESTIGATION OF GREY WATER TREATMENT PERFORMANCE IN A VERTICAL FLOW CONSTRUCTED WETLAND", which he prepared after fulfilling the requirements specified in the associated legislations, before the jury whose signatures are below.

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To my instructors,

FOREWORD

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ABBREVIATIONS

GW	: Grey water
NBSs	: Natural-based solutions
CWs	: Constructed wetlands
PE	: Population equivalent
ABR	: Anaerobic Bioreactor
TSS	: Total Suspended Solids
Al	: Aluminum
BAF	: Biologically Aerated Filters
UN	: United Nations
BOD	: Biochemical Oxygen Demand
Ca	: Calcium
Cl	: Chlorine
CO_2	: Carbon dioxide
VFCW	: Vertical Flow Constructed Wetland
Fe	: Iron
ISKI	: Istanbul Water and Sewerage Administration
COD	: Chemical Oxygen Demand
MBBR	: Moving Bed Biofilm Reactor
MBR	: Membrane Bioractor
Mg	: Magnesium
Mn	: Manganese
N	: Nitrogen
Na	: Sodium
NH_4-N	: Ammonia Nitrogen
NO_3	: Nitrate
NTU	: Nephelometric Turbidity Unit
OM	: Organic Matter
PO_4-P	: Phosphatex
RBC	: Rotating biodisc
SBR	: Sequential Batch Reactor

SO_4 : Sulphate
TN : Total Nitrogen
TP : Total Phosphorus
VSS : Volatile Suspended Solids
UASB : Upflow Sludge Bed Reactor
UV : Ultraviolet
XOC : Xenobiotic Compounds
Zn : Zinc

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INVESTIGATION OF GREY WATER TREATMENT PERFORMANCE IN A VERTICAL FLOW CONSTRUCTED WETLAND

SUMMARY

The depletion and unconscious consumption of water, which is an indispensable element for vital activities, has become a global problem due to the increasing world population and industrialization. The decrease in precipitation as a result of climate change has made this problem even more challenging. A significant portion of the world's population currently has difficulty in accessing potable clean water resources. Moreover, it is reported that there will be a further increase in this human population deprived of this water in the coming years. Although countries put forward strategic plans on a national and international scale so that this problem does not turn into a serious crisis, they will face this crisis unless more measures are taken. The sustainability goals of the United Nations are a part of the solution proposals put forward against this problem. As resources should be used correctly and efficiently, making these resources reusable is one of the most important solutions. The reuse help reduces the risks of negativity in the process leading to the water crisis.

Treatment of GW, which constitutes a large part of domestic WW and has a low pollution load, for reuse will reduce the burden on existing facilities and contribute to sustainable wastewater management. Thus, treated WW, which is discharged into water bodies and has the potential to cause environmental pollution to a certain extent, will turn into a valuable input. The treatment of these GWs, which do not require advanced treatment, using natural treatment technologies will further increase this positive contribution. Because natural purification technologies; They can imitate natural processes and offer an effective treatment performance without requiring energy, reinforced concrete structure and mechanical equipment. For all these reasons, in this thesis, the conversion of gray water into reusable water using a natural treatment technology has been examined.

GWs, which are characterized as weak or strong according to their type, have a great potential for reuse. GWs can become usable water directly or indirectly by removing the disease-causing pollutants and pathogens in its content. Thus, the pressure on water resources may decrease somewhat. Moreover, since the load on WW treatment plants will decrease, a serious economic loss will be prevented.

In this study, the treatment of GW, which is a valuable resource, by collecting it with discrete systems for reuse in CWs, which is one of the natural treatment systems, was investigated. Thus, it is aimed to fill this gap by offering a sustainable and environmentally friendly treatment method for Türkiye, which is also under water stress. Presenting it as a realistic solution to prevent environmental disasters such as mucilage will also be decisive in terms of Türkiye's environmental policies. By obtaining effective treatment efficiencies, an incentive will be created for the use of these technologies, especially in areas with low urbanization. In this direction, the GW of a large hotel in Taksim, Istanbul, was collected and then characterized, and these GWs were treated in the vertical subsurface flow constructed wetland (VFCW)

installed in the laboratory. The quality of the treated GW in the reactor was determined and thus the GW treatment performances of the wetland were investigated. Characterization results were compared with a previous study by TÜBİTAK and no big difference was observed. However, the decrease in the number of guests due to the pandemic caused a decrease in N and P values. On the other hand, higher than average values were obtained in some COD measurements due to their lower water consumption.

The VFCW bed, where filtration and adsorption will take place, was created by considering the design concepts in the literature. The system was fed with gray water for 2 weeks before the main experiment plan was carried out. Thus, biofilm growth was provided for the activity of microorganisms. The reactor in which *Cyperus alternifolius* was planted was fed with GW for 4 hours until saturation throughout the operation. The feed mode was operated at HLR 204 mm d^{-1}, SPV 102 L m^{-2} and SHLR 0.45 L m^{-1} min^{-1}. After the feed mode, the reactor was slowly emptied and rested for the second cycle. After the second cycle, the system was put into rest mode for 8 hours.

As a result of the treatment in the VFCW, satisfactory results were obtained in the removal of organic matter. Especially in N removal, no negative results were obtained compared to other studies. The most important removal mechanisms for VFCW are adsorption, sorption, filtration and microbial activity. On the other hand, the VFCW system is inferior to horizontal subsurface flow constructed wetlands (HFCW). The most important removal mechanisms for VFCW systems are adsorption, sorption, filtration and microbiological activity. On the other hand, the advantage of the VFCW system over the horizontal subsurface flow artificial wetland (HFCW) systems is that nitrification is enabled by creating aerobic conditions in the system according to the feeding mode. As for the average removal performances of the VFCW reactor, satisfactory removal efficiencies such as 85% for COD, 45% for TN, 81% for TP and 93% for NH4-N were obtained. The load removal efficiencies were 15.6 $g/m^2 \cdot d$ for COD, 1.1 $g/m^2 \cdot d$ for TN and 0.4 $g/m^2 \cdot d$ for TP. TP concentrations decreased rapidly, mostly because it was adsorbed on the filter media. When nitrogen removal kinetics are examined, a decrease in NH_4-N concentrations was observed with an increase in NO_3-N concentrations at the beginning. 1 hour after the start of the starting samples, NO_3-N concentrations decreased and TN removal was observed. These results showed that simultaneous nitrification and denitrification occurred in the system. There are two possible explanations for this situation. First, the feed mode has a major effect on oxygen transfer to the VFCW, and operating the reactor with the filter media partially or completely saturated causes the development of oxygen-free zones. Therefore, it can be said that operating the system with fully saturated feeding mode followed by a rest period creates a hybrid system effect in which aerobic and anoxic zones are developed that allow simultaneous nitrification and denitrification. The second is aerobic denitrification. Aerobic denitrification is a process that can simultaneously use both oxygen and nitrate as electron acceptors and therefore can reduce nitrate in the presence of oxygen. This process can occur in environments where there are fluctuations in oxygen concentrations and a shortage of carbon sources. Considering the feeding mode and the poor quality of the raw GW used, that is, the carbon source is not too much, it can be said that the system performs the aerobic denitrification process.

DİKEY AKIŞLI BİR YAPAY SULAK ALANDA GRİ SU ARITMA PERFORMANSININ DEĞERLENDİRİLMESİ

ÖZET

Yaşamsal faaliyetler için vazgeçilmez bir unsur olan suyun kaynaklarının tükenmesi ve bilinçsizce tüketilmesi, artan dünya nüfusu ve sanayileşmeden dolayı küresel bir sorun haline gelmiştir. İklim değişikliği neticesinde yağışların azalması da bu sorunu daha da zorlayıcı hale getirmiştir. Dünya nüfusunun ciddi bir kısmı şu an için içilebilir temiz su kaynaklarına ulaşmakta zorlanmaktadır. Dahası, gelecek yıllarda bu sudan mahrum olan bu insan popülasyonunda daha da artışın olacağı bildirilmektedir. Bu sorunun ciddi bir krize dönüşmemesi için ülkeler, ulusal ve uluslararası çapta stratejik planlar ortaya koysa da daha fazla önlem alınmadığı takdirde bu krizle karşı karşıya kalacaktır. Birleşmiş Milletler'in sürdürülebilirlik hedefleri ise bu soruna karşı ortaya konulmuş çözüm önerilerinin bir parçasıdır. Kaynakların doğru ve verimli kullanılması gerektiği gibi, bu kaynakların yeniden kullanılabilir hale dönüştürülmesi en önemli çözümlerden bir tanesidir. Arıtılmış atıksuların yeniden kullanılabilir hale gelmesi, su krizine giden süreçteki olumsuzluk risklerini azaltmaya yardımcı olacaktır.

Evsel atıksuların büyük bir bölümünü oluşturan ve kirlilik yükü az olan gri suların yeniden kullanılmak üzere arıtılması mevcut tesislerdeki yükü azaltacak ve sürdürülebilir atıksu yönetimine katkıda bulunacaktır. Böylece, su kütlelerine deşarj edilen ve belli bir oranda yine çevresel kirlilik oluşturma ihtimali olan arıtılmış atıksular, değerli bir girdiye dönüşecektir. İleri derecelerde arıtma gerektirmeyen bu gri suların doğal arıtma teknolojileri kullanılarak arıtılması, bu olumlu katkıyı daha da artıracaktır. Çünkü doğal arıtma teknolojileri; enerji, betonarme yapı ve mekanik ekipman gerektirmeden doğal süreçleri taklit eder ve etkili bir arıtma performansı sunabilirler. Tüm bu nedenlerden dolayı bu tez çalışmasında gri suların bir doğal arıtma teknolojisi kullanılarak yeniden kullanılabilir suya dönüşmesi irdelenmiştir.

Çeşidine göre zayıf veya güçlü olarak nitelendirilen gri sular, yeniden kullanım için büyük bir potansiyele sahiptir. Gri sular, içeriğindeki hastalık yapıcı kirletici ve patojenlerin giderilmesiyle doğrudan veya dolaylı olarak kullanılabilir bir su haline gelebilirler. Böylece su kaynaklarına olan baskı bir miktar azalma gösterebilir. Dahası, atıksu arıtma tesislerine gelen yük azalacağından ciddi bir ekonomik kayıp önlenecektir.

Bu çalışmayla, değerli bir kaynak olan gri suların ayrık sistemlerle toplanarak doğal arıtma sistemlerinden birisi olan yapay sulak alanlarda yeniden kullanılmak üzere arıtılması araştırılmıştır. Böylece, su stresi altında olan Türkiye için de sürdürülebilir ve çevre dostu bir arıtma yöntemi sunularak bu boşluğun doldurulması amaçlanmıştır. Müsilaj gibi çevresel felaketlerin önlenebilmesi için gerçekçi çözüm olarak sunulması Türkiye'nin çevresel politikaları açısından da belirleyici olacaktır. Etkili arıtma verimlerinin elde edilmesiyle, özellikle kentleşmenin az olduğu bölgelerde bu teknolojilerin kullanılması için bir teşvik oluşturulması sağlanacaktır. Bu doğrultuda, İstanbul Taksim'deki büyük bir otelin gri suları toplandıktan sonra karakterizasyonu yapılmış ve bu gri sular laboratuvarda kurulan dikey yüzey altı akışlı yapay sulak alan

(DYSA) reaktöründe arıtılmıştır. Reaktörde arıtılmış gri suyun kalitesi belirlenmiş ve böylece sulak alanın gri su arıtma performansları incelenmiştir. TÜBİTAK'ın daha önceden yapılmış bir çalışmasıyla karakterizasyon sonuçları karşılaştırılmış ve büyük bir farklılık görülmemiştir. Bununla birlikte, pandemiden kaynaklı misafir sayısındaki azalış, azot ve fosfor değerlerinde azalmaya sebep olmuştur. Buna karşın, daha az su tüketimleri nedeniyle bazı KOİ ölçümlerinde ortalamalanın üzerinde değerler elde edilmiştir.

Filtrasyon ve adsorpsiyonun gerçekleşeceği sulak alan yatağı literatürdeki tasarım konseptleri göz önünde bulundurularak oluşturulmuştur. *Cyperus alternifolius* bitkisinin dikildiği reaktör ana deney planı gerçekleştirilmeden önce sistem 2 hafta gri su ile beslenmiştir. Böylece mikroorganizmaların aktivitesi için biyofilm büyümesi sağlanmıştır. Reaktör, işletme boyunca, doyuncaya kadar 4 saat gri su ile beslenmiştir. Besleme modu, HLR 204 mm/d, SPV 102 L/m^2 ve SHLR 0,45 L/m·dk olarak çalıştırıldı. Besleme modunun ardından reaktör yavaşça boşaltıldı ve ikinci döngü için dinlendirilmiştir. İkinci döngünün ardından sistem 8 saat dinlenme moduna alınmıştır.

Sulak alan reaktöründeki arıtım neticesinde, organik maddelerin giderimi konsunda tatminkar sonuçlar elde edilmiştir. Özellikle azot gideriminde diğer çalışmalara nazaran olumsuz bir sonuç elde edilmemiştir. DYSA sistemleri için en önemli giderim mekanizmaları, adsorpsiyon, sorpsiyon, filtrsayondur. Atıksudaki nütrientlerin bitkiler tarafından besin maddesi olarak kullanılmasıyla fitoremediasyon süreci gerçekleşebilir. Bununla beraber, hasat zamanında bitkilerin hasat edilmemesi, bitki bünyesine alınan nütrietlerin geri salınımına neden olacağından, bu durumun giderim prosesi olarak sayılamayacağı düşüncesi de bazı çalışmalarda belirtilmiştir. Öte yandan, DYSA sisteminin yatay yüzey altı akışlı yapay sulak alan (YYSA) sistemlerine göre avantajı ise besleme moduna göre sistemde aerobik koşulların oluşturulmasıyla nitrifikasyona olanak sağlanmıştır. DYSA reaktörünün ortalama giderim performanslarına gelince, KOİ için %85, TN için %45, TP için %81, NH_4-N için %93 gibi tatmin edici giderim verimleri elde edilmiştir. Yük giderme verimlilikleri ise, KOİ için 15,6 g/m^2·d, TN için 1.1 g/m^2·d, TP için 0.4 g/m^2·d idi. TP konsantrasyonları çoğunlukla filtre ortamına adsorbe olması nedeniyle hızla düşmüştür. Azot giderim kinetikleri incelendiğinde ise, başlangıçta NO_3-N konsantrasyonlarındaki bir artışla birlikte NH_4-N konsantrasyonlarında azalma gözlemlenmiştir. Çıkış numunelerinin alınmaya başladıktan 1 saat sonra NO_3-N konsantrasyonları azalmış ve TN giderimi gözlenmiştir. Bu sonuçlar, sistemde eş zamanlı nitrifikasyon ve denitrifikasyonun meydana geldiğini göstermiştir. Bu durumun iki olası açıklaması olabilir. Birincisi, besleme modunun DYSA reaktörüne oksijen transferinde büyük bir etkiye sahip olması ve reaktörün filtre ortamının kısmen veya tamamen doymuş olarak çalıştırılmasının oksijensiz bölgelerin gelişmesine neden olmasıdır. Bu nedenle, sistemin tam doygun besleme modu ve ardından dinlenme periyodu ile çalıştırılmasının, eş zamanlı nitrifikasyon ve denitrifikasyona olanak sağlayan aerobik ve anoksik bölgelerin geliştiği hibrit bir sistem etkisi yarattığı söylenebilir. İkincisi ise aerobik denitrifikasyondur. Aerobik denitrifikasyon, elektron alıcıları olarak hem oksijeni hem de nitratı aynı anda kullanabilen ve bu nedenle oksijen varlığında nitratk indirgeyebilen bir işlemdir. Bu süreç, oksijen konsantrasyonlarındaki dalgalanmaların ve karbonun kaynağındaki yetersizlik durumunun mevcut olduğu ortamlarda gerçekleşebilir. Sistemin besleme modu ve sistemde kullanılan ham gri suyun zayıf nitelikli olması, yani karbon kaynağının çok fazla olmaması düşünüldüğünde, sistemin aerobik denitrifikasyon sürecini gerçekleştirdiği söylenebilir.

Tüm bu hususlar göz önünde bulundurularak, tasarıma bağlı olarak işletme modunun da bu sistemlerde son derece belirleyici bir rolü olduğu söylenebilir. Besleme modundaki optimizasyonlarla arıtma verimliliklerinin yükseltilebileceği ve hibrit sisteme ihtiyaç duyulmadan tek bir sistemde gri suların arıtılmasının mümkün olabileceği belirlenmiştir.

Bu sonuçlar neticesinde, “Sürdürülebilir Kalkınma” ve “Yeşil Dönüşüm” hedefleri olan Türkiye’nin, bilhassa kırsal bölgelerinde bu tür arıtma sistemlerini yaygınlaştırması sayesinde atıksuyun neden olduğu çevresel felaketlerin önüne geçmesi mümkündür. Diğer YSA sistemlerine göre sinek ve koku gibi avantajlarının da bulunması ve daha güvenilir olması nedeniyle bu sistemlerin yaygınlaştırılması önerilmektedir.

1. INTRODUCTION

A vital resource to sustain life activities, water is used directly or indirectly in every field, such as domestic use, urban consumption, industry, and agriculture (Gross et al., 2015). Today, however, one out of every three people cannot reach and consume potable water. Moreover, by 2050, it is predicted that close to 6 billion people will be living in areas where water is scarce for at least 1 month of the year. (UN.Water, 2021). Hence, efficient management for all water is a universal issue that is attention-garnering from a variety of international institutions and organizations.

When also considering climate change, water-saving and effective use of water sources have great importance in arid areas (Heyns, 2000; Roldán-Cañas et al., 2021). Around the world, over two-thirds of the total water withdrawal is used by agricultural production (Boretti & Rosa, 2019). Industry, on the other hand, has an average of about 22% water withdrawal (Sachidananda & Rahimifard, 2012). As for the domestic water usage rate, this rate is this rate is the rest 8% of global water consumption (Inglezakis et al., 2016).

Ever since the reuse of wastewater (WW) has gained attention, domestic WW has been categorized as light greywater (GW) which occurs from bathrooms, launderette, etc, and black water from toilets (Patil et al., 2022; van Voorthuizen et al., 2008). One way to manage the impact of household water consumption is with the reclamation and reuse of GW using undersize and on-site facilities (Gross et al., 2015).

With the objective to reduce the pressure on existing infrastructure, non-conventional WW treatment technologies have been developed. Due to the problems caused by the difficulties and limitations of traditional systems, the idea of separating the installations in buildings for the treatment of GW has emerged. (Abdalla et al., 2021). Recently, nature-based solutions (NBSs) stand out as they have the potential to counter scary pressures on climate change and sustainability (Kabisch et al., 2017). Constructed wetlands (CWs) are at the epicenter of NBSs (Takavakoglou et al., 2022).

Investigating of GW, which is considered to be low-strength WW with high reuse and application potential, recycling in CWs, has become an endeavor to be considered.

1.1 Purpose of Thesis

Sustainable management of resources is essential in order to prevent drought due to increasing water stress and climate change (Brekk, 2009; Çapar & Türkeş, 2019; Schmitt, 2010). One of the solutions that can be brought in this context is the treatment and reuse of WW by using eco-friendly nature-based systems (A. I. Stefanakis, 2019). Therefore, in recent years, the results of many studies evaluating WW treatment performances in CWs have been presented and new research is being studied.

GW reuse is an old practice. This practice is still practiced in areas where water is scarce. With the widespread use of the GW reuse practices and ensuring efficient management, resources can be protected and environmental pollution caused by untreated GW can be prevented. (Oteng-Peprah et al., 2018).

The aim of the thesis is to examine the GW treatment performances of CW systems, which have many advantages over conventional systems, to determine the reuse fields of treated GW in these systems, to reveal the gaps in GW technologies in Türkiye and to offer solutions regarding this issue.

1.2 Scope of Thesis

As a result of urbanization and industrialization, “centralized” systems have initially been adopted for WW treatment. At present, it has been argued that energy management in the “centralized” approach is not an optimal sustainable strategy from the emphasis on WW reuse. On the contrary, decentralized systems are a more viable solution for wastewater distribution. Because in these systems, there is a gravity flow of wastewater. After the WW is treated, GW can be reused in applications such as irrigation or toilet flushing, by means of this energy-free flow (Austin & Yu, 2016). On the other hand, 65% of the WW consists of GW. Up to 50% of this GW consists of light GW, which is not difficult to treat (Ghaitidak & Yadav, 2013b). This may enable the low-cost treatment of light GWs in CWs and the reuse of these treated GWs.

Within this framework, the investigation of the treatment performances of a vertical flow CW system fed with the hotel GW constitutes the scope of this dissertation. In addition, it is the determination of suitable reuse areas according to the quality of the treated GW.

The objectives to be achieved as a result of these studies was as follows:

1. To form a quantitative study that evaluates the performances of CWs to treat or purify GW with the aim reuse,
2. To contribute to the literature on the vertical subsurface flow CW type, which specifically treat GW,
3. To investigate the effect of hydraulic conditions on the treatment performances and the CW system,
4. To investigate the possible effects of hydraulic conditions on microbial activities,
5. To contribute to the literature on the plant species used,
6. To direct future studies on optimization,
7. To reach usable data for pilot and full-scale plants,
8. To determine suitable reuse areas according to the effluent quality,
9. To reduce consumption and pollution of clean water resources through recycling and reuse,
10. To identify possible risks that may occur as a result of reuse,
11. To contribute to national and global sustainability goals.

2. LITERATURE REVIEW

2.1 Introduction of Wetlands

Wetlands are not wastelands (Mitsch, 1994). Wetlands are characterized as a transition region between land and water systems, and it is not easy to define the boundaries of their due to their time-wise, spatial, and ecological differences (Kent, 2001; Vymazal, 2022). Water entering wetlands where the water is stored or can be possibly stored comes from four potential sources: precipitation, surface run-off, stream, and groundwater (Haslam, 2003). Protecting and restoring the wetlands which contain many hydrological, physical, chemical, biological, botanical, animal, economic, landscape, and social values, have a great importance in terms of the sustainability goals of countries (Alikhani et al., 2021). Socio-cultural and ecological values of wetlands are shown in Figure 2.1.

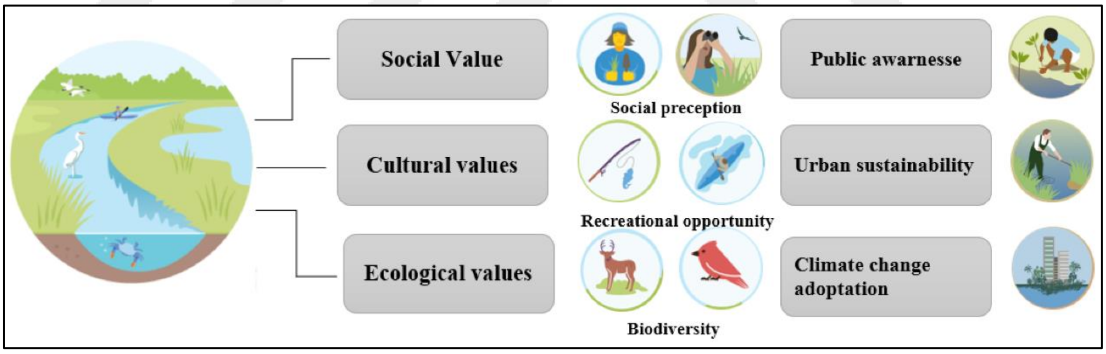


Figure 2.1: Socio-cultural and ecological values of wetlands (Alikhani et al., 2021).

Furthermore, wetlands of the Mother Nature can remedy water quality by slowing runoff and removing or grabbing non-organic nutrients, consuming organic wastes, and reducing the content of suspended solids before they arrive in offshore waters (Donna An et al., 1996; Mitsch et al., 2012). Natural wetlands have a great importance in the treatment of wastewater since ancient times. Although it was used for the disposal of WW at first, it started to be used for the treatment of WW in the mid-1900s. (Brix, 1995; Vymazal, 2022). In 1953 and the next years, Dr. Käthe Seidel studied and experimented on the reaction of macrophytes and substrate environment in WW treatment in practices she called the "hydrobotanical methods" (Vymazal, 2008).

However, the studies with wetlands showed the difficulties in maintenance and performance of the system. Therefore, natural wetlands used to improve water quality have given way to CWs, which have been advanced since half a century (Skrzypiec Bcef & Gajewska Ad, 2017; Vymazal, 2022). Moreover, the number of applications to take advantage of the potential benefits of wetlands is increasing. This allows further exploration of the current and potential impacts of wetlands in treatment technologies. (A. I. Stefanakis, 2020).

2.2 Constructed Wetlands (CWs)

Constructed wetlands (CWs), also called treatment wetlands, are designed to take advantage of natural treatment processes and to remove the contaminants in WW in a controlled manner (Wu et al., 2014). Technologies like these, which mimic natural wetlands functionally and morphologically, are removed damaging pollutants in WW by simulating the processes in wetlands (Español et al., 2015; Masi et al., 2018; Ozimek & Czuprynski, 2003).

CWs, which are an environmentally friendly treatment technology with minimal negative environmental impact due to their use of natural processes (Dan et al., 2011), are mainly used in rural areas, remote regions, and smaller areas in order to provide treatment services (Zhao et al., 2020). Focussing on low-cost and high-efficiency WW purification, CWs has received considerable attention from engineers and scientists during the past decades for their advance. In the earlier stages of CW development, some CW types were greatly favored types, such as free-water superficial wetlands (FWS) and horizontal flow wetlands (HF) (Wu et al., 2014), in order to treat domestic/municipal WW (Morari & Giardini, 2009).

Presently, researches focus on the modification and optimization of CWs. Because effective and long-term treatment performances in wetlands have not been achieved yet. In addition, the sustainable operation of these systems is still a problem. Morever, removal performance of CWs is substantially based on the optimum operating conditions (loading rates, hydraulic regimes, feeding modes, implementation plan, etc.). On the other hand, system components in CWs, such as species planted and substrate matrix, are critical influencing factors to their treatment performance. Because they are considered to be the significant design choice. And also, they influence the removal performances in the medium and long term. Furthermore, removal processes in CWs, like adsorption, sedimentation, microbial activities, and plant uptake, are usually affected by environmental conditions (e.g., temperature, oxygen/carbon sources, pH). Meanwhile, CWs as natural passive cannot be much advised owing to the large area requirement. In recent years, the number of experimental research and applications on these factors affect the performance of CWs has increased (Kassa, 2019; Parde et al., 2021; Wu et al., 2014).

Likewise, the volume of information in the literature on possible solutions proposed to achieve the desired removal rates and reduce the effects of these factors has increased significantly. Specifically, model combinations and hybrid systems related to subsurface flow CWs have led to various CW designs and configurations. However, although the efficiency of CWs in WW treatment has been proven, there are major shortcomings in the effective implementation and efficient management of CWs in some developed and developing countries (Kassa, 2019).

2.2.1 Benefits and limitations of constructed wetlands

Benefits obtained from CWs include, in addition to purification capacity, water storage, flood control, habitat diversity, recreation, and an aesthetic environment. Therefore, both CWs and natural wetlands have alike bionomical functions, although CWs could be identified as the more eco-encombered environments in comparison with natural wetlands (Stefanakis et al., 2014). Gharmandi et al. compared 186 CWs and natural wetlands and reported that CWs hold higher value compared to others, particularly in points of flood control and water purification, while they enhance the possibility of biodiversity conservation and diversifying habitats or vegetation in a region (Ghermandi et al., 2009). Although not all wetland types can perform all roles and profits, they present various benefits. The following benefits can be obtained from CWs (Omondi & Navalia, 2020):

- In the case of GW, a significant increase in water quality
- Recovery and reuse of GW
- Reducing the load on WW treatment plants
- Sustainable cycling of polluting organic and inorganic pollutants in WW
- Flood control
- Habitat

- Recreation
- Educational recreation
- Landscape opportunity

2.2.2 Constructed wetlands classification

Wetlands constructed according to their mission and goal can be classified into three main functions: WW treatment, flood control and habitat (Rousseau et al., 2008).

Based on the targeted pollutant, CWs in many different types are engineered and constructed to maximize removal rates (Negi et al., 2022). CWs classified to their hydrology and vegetation are shown in Figure 2.2.

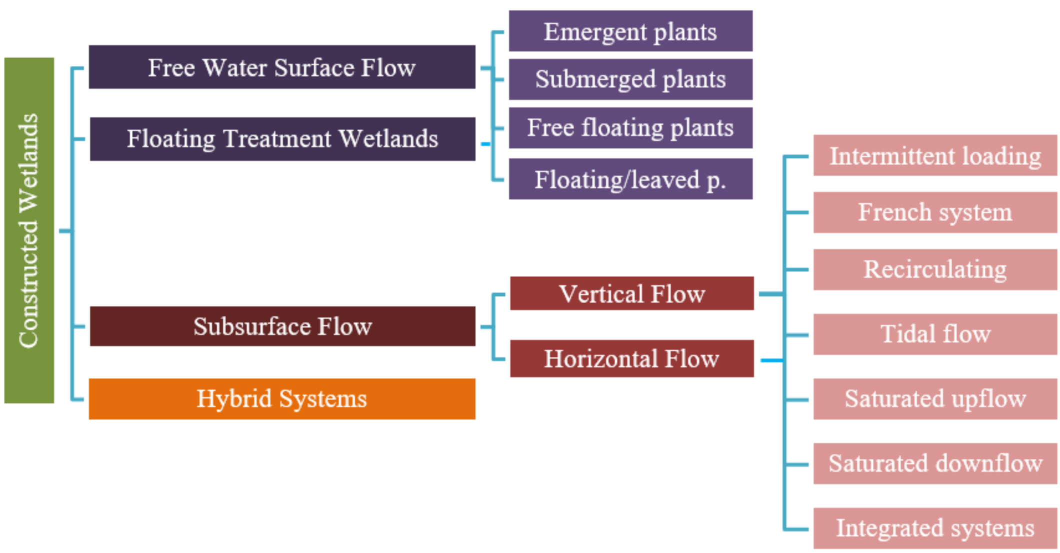


Figure 2.2: Types of constructed wetlands (A. I. Stefanakis, 2018).

The main differences between CWs, which are generally characterized in two main classes as FWS and SSF, are listed in Table 2.1.

Table 2.1: Differences between FWS and SSF (Polprasert & Kittipongvises, 2011).

FWS (Free water surface flow)	SSF (Subsurface flow)
With surface flow	With subsurface flow
Shallow water	Water is in a porous medium
Floating, emergent, and submerged plants	Emergent plants
Impermeable layer	Impermeable layer
Low flow rate	Higher flow rate
Media with mostly soil, sand, grave	Media with sand and gravel
Odor and mosquito problem	Less odor and mosquito problem

2.2.2.1 Free water surface constructed wetlands (FWS)

FWS CW systems typically consist of shallow ponds or open channels with a nonpermeable bed (e.g., clay or geo-membranes) to prevent leakage to aquifers and a submerged soil-sediment layer (usually 30–40 cm thickness) to support plant roots This type of CW also includes delivery structures (e.g., delivery and discharge orifice) (Polprasert & Kittipongvises, 2011). There are horizontal flow in FWSs. The flow heads toward superficially and sinuously from intake to exit at low velocity. The typical flow path for FWSs have most ecological potential and have most resemblance to natural wetlands is illustrated in Figure 2.3.

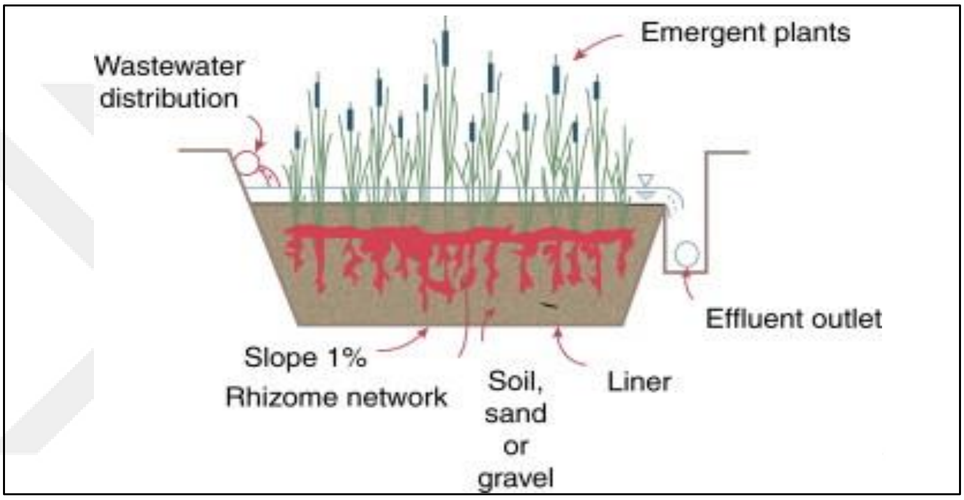


Figure 2.3: Flow path of a FWS system (Polprasert & Kittipongvises, 2011).

2.2.2.2 Horizontal subsurface flow constructed wetlands (HFCWs)

The WWs, in horizontal subsurface flow constructed wetlands (HFCW) which are also called as reed bed, drain horizontally in wetland media through porous media In the HFCW, aerobic environment occurs in the rhizosphere. Thus, organic matter (OM) degrades due to anaerobic conditions (Polprasert & Kittipongvises, 2011).

To build these systems, a land area of 5-10 m^2/PE (Population Equivalent) is required. This is higher than the land requirement of VFCWs. However, the denitrification potential of HFCWs is much better. Besides, this systems are used to treat a variety of WW, such as industrial, agricultural and mine WWs and they are commonly used in the America and Europe. In contrast to FWS systems, HFCWs have higher investment costs, although land area requirement is less than FWS (A. Stefanakis et al., 2014; A. I. Stefanakis, 2018). Figure 2.4 is shown a typically HFCW.

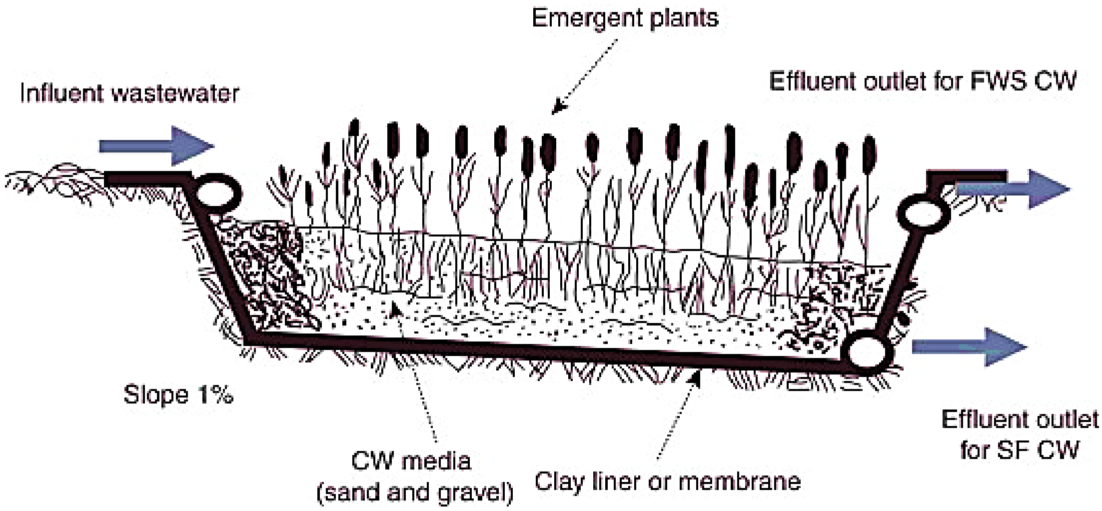


Figure 2.4: Flow path of a HFCW system (Polprasert & Kittipongvises, 2011).

2.2.2.3 Vertical subsurface flow constructed wetlands (VFCWs)

Vertical flow constructed wetlands (VFCWs) in which WW is vertically fed from the top of the system and drained from the bed, offer an aerobic environment, therefore, obtained high removal rates for COD, nitrification, and others. The land area requirement for these types of CWs is 1–3 m^2/PE. And this is less than HFCWs. However, the maintenance requirements are high. The flow path of the VFCW is illustrated in Figure 2.5.

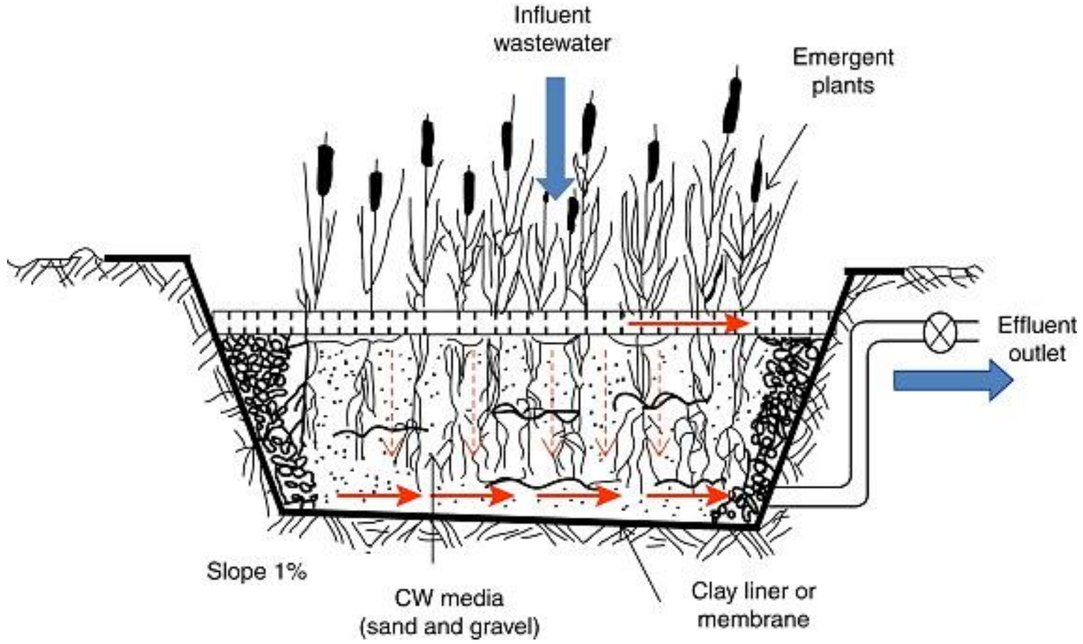


Figure 2.5: Flow path of a VFCW system (Polprasert & Kittipongvises, 2011).

2.2.2.4 Hybrid constructed wetlands (H-CWs)

Hybrid constructed wetlands (H-CWs) have been designed as a multi-stage CW in order to enhance pollutant removal rates. H-CWs, which are often an integration of HFCW and VFCW, combine the advantages of CW integrated. Therefore, they have high treatment performance (Vymazal & Kröpfelová, 2015). An example with three-stage of HCWs is shown in Figure 2.6.

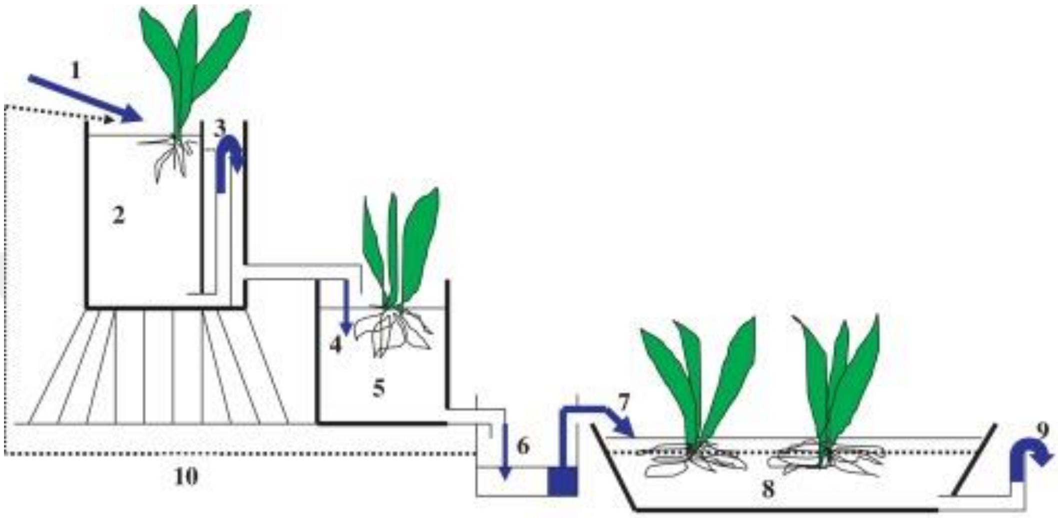


Figure 2.6: Three-stage hybrid constructed wetland (Vymazal & Kröpfelová, 2015).

1: WW, 2: saturated VF, 3: standpipe, 4: outflow, 5: VF, 6: outflow,
7: inflow, 8: HF, 9: final outflow, 10: recirculation

2.2.2.5 Constructed floating wetlands (CFWs)

Constructed floating wetlands (CFWs), which are a phytoremediation technology as a type of in-situ treatment system, are a cost-effective kind of CW to treat various types of WW. The CFWs can successfully treat WW in several ways: by filtration, by the absorption of pollutants by the plants used, and by degradation in the microbial environment that occurs. These systems have an important advantage that they do not require extra land. In addition, they can easily continue their duties in different hydrological conditions and situations. Aquatic plants that grow on a floating bed develop roots in the water column. On the other hand, there are factors that limit these systems, such as mikrobial activity (Colares et al., 2020; Shen et al., 2022). The CFWs is shown in Figure 2.6.

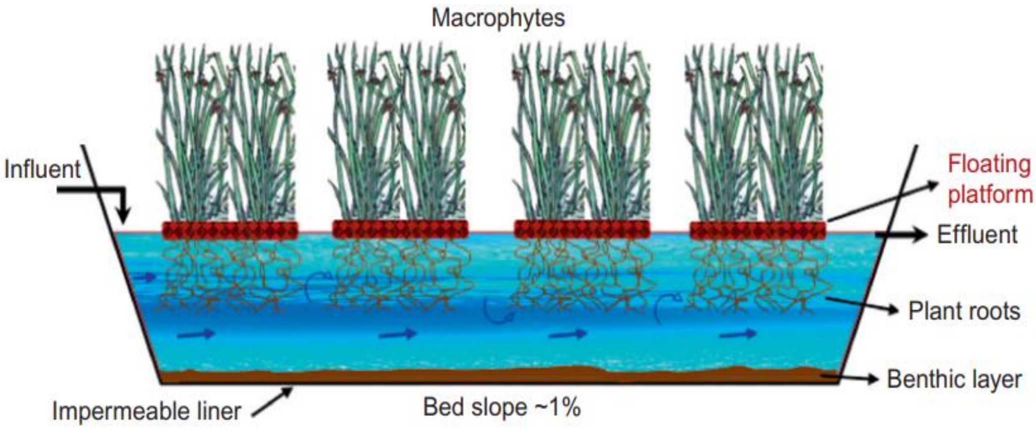


Figure 2.7: Flow path of a CFW system (A. Stefanakis et al., 2014).

2.3 Vertical Subsurface Flow Constructed Wetlands (VFCWs)

VFCWs, which are very similar in principle to conventional trickling filters, have subsurface flow like HFCW systems. Due to the oxygen transfer capacity and less area requirement of these systems, research on various modifications of these systems has gained increasing popularity (Şener, 2007). Besides, owing to the high nitrification potential of VF systems, the use of which has become increasingly common in the last 30 years, WW enters the wetland periodically and is discharged by gravity (A. I. Stefanakis & Tsihrintzis, 2012). This feeding strategy provides the necessary electron acceptor for OM and N removal by providing O_2 input to the wetland. The denitrification capabilities of VF systems are relatively limited due to the inadequacy of the carbon source depending on the nutrients in the WW and the wetland substrate (Kaur et al., 2020). A classical VFCW is shown in Figure 2.8.

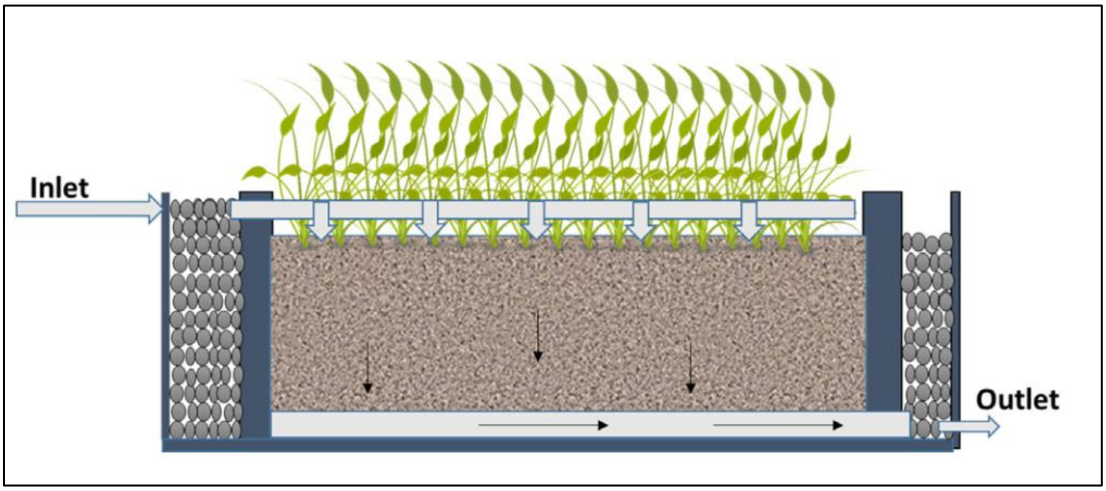


Figure 2.8: Flow path of a classical VFCW system.

2.3.1 Treatment processes

The WW treatment process of VFCW systems can be explained by the complex relationship of many components. VFCW reactors with an impermeable bottom are filled up with bed material of different sizes and properties, and then planted with macrophytes, which have a high capacity to hold pollutants and diffuse oxygen into the system.

The main purpose of VFCW systems, which also benefit from the plants and substrate materials in addition to the some components in conventional systems, is to optimize the activities of microorganisms in the system and as a result, to provide biological transformation of pollutants. In VF wetlands, microbial growth in the system is supported by optimizations and components such as plants, media materials and different feeding modes, thus paving the way for various treatment processes such as adsorption, volatilization and biochemical conversion of pollutants in WW (Kataki et al., 2021; Montgomery, 2004). Figure 2.9 summarizes the processes and important factors in VFCWs. Additionally, many media materials are used in VFCWs for filtration. Materials such as gravel, sand, zeeolite and limestone, which are washed and cleaned before use, are used as media (Sijimol & Joseph, 2021). Also, it has been reported that many natural wetland plants can be used in artificial wetlands (Vymazal, 2011).

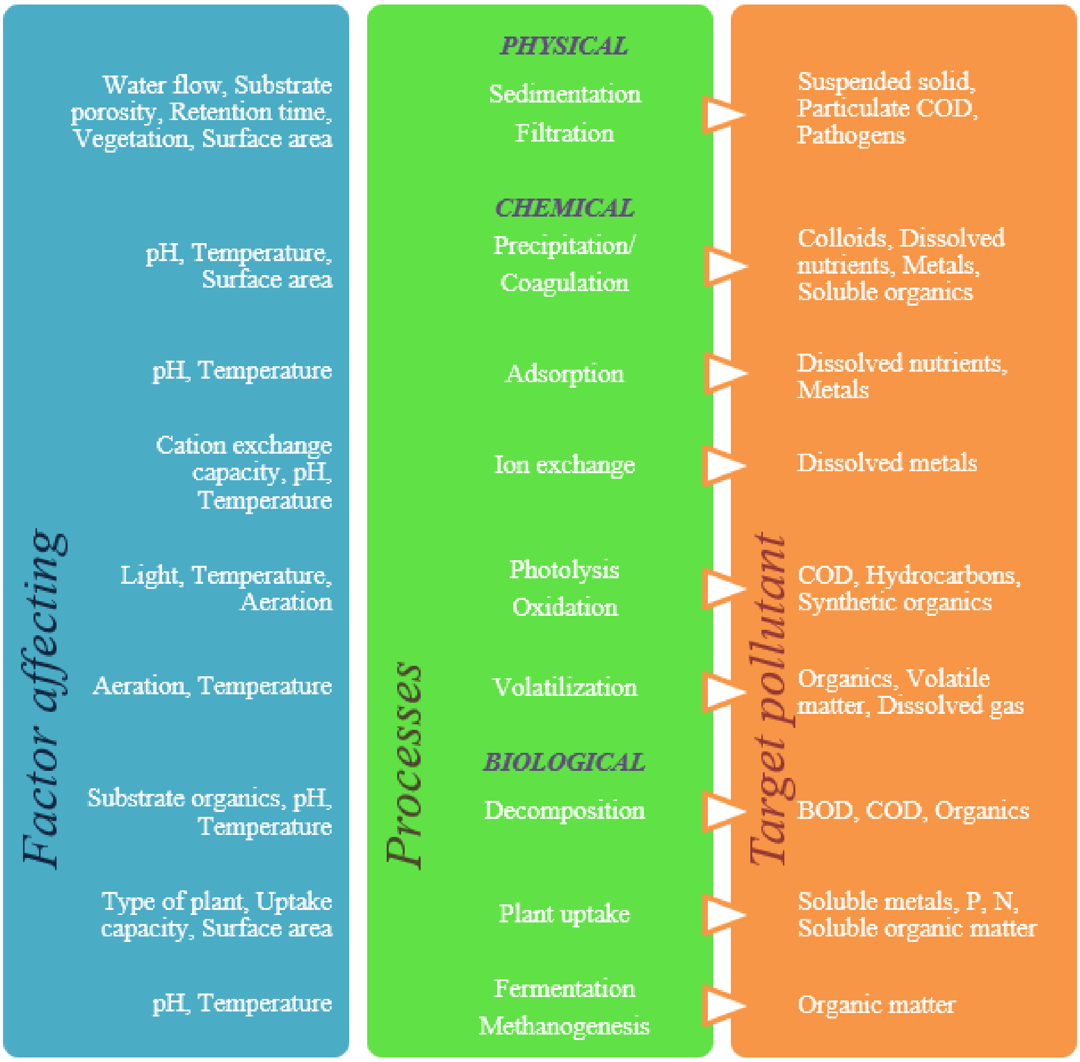


Figure 2.9: Mechanisms, processes and target pollutant in VFCWs (Kataki et al., 2021).

Another difference of these systems compared to HFCW systems, where WW is dosed vertically from above the wetland, is the aerobic conditions. Aerobic and anaerobic conditions are created at different stages by intermittent dosing (4-10 times per day) in the wetland. During the filling phase, the WW is filtered through the unsaturated filter medium; In the discharge phase, the WW is drained from the system and thus air fills the wetland. Thus, the substrate provides a basis for adsorption and biofilm growth (Tilley et al., 2008). Functions of a plant in the VFCW are shown Figure 2.10.

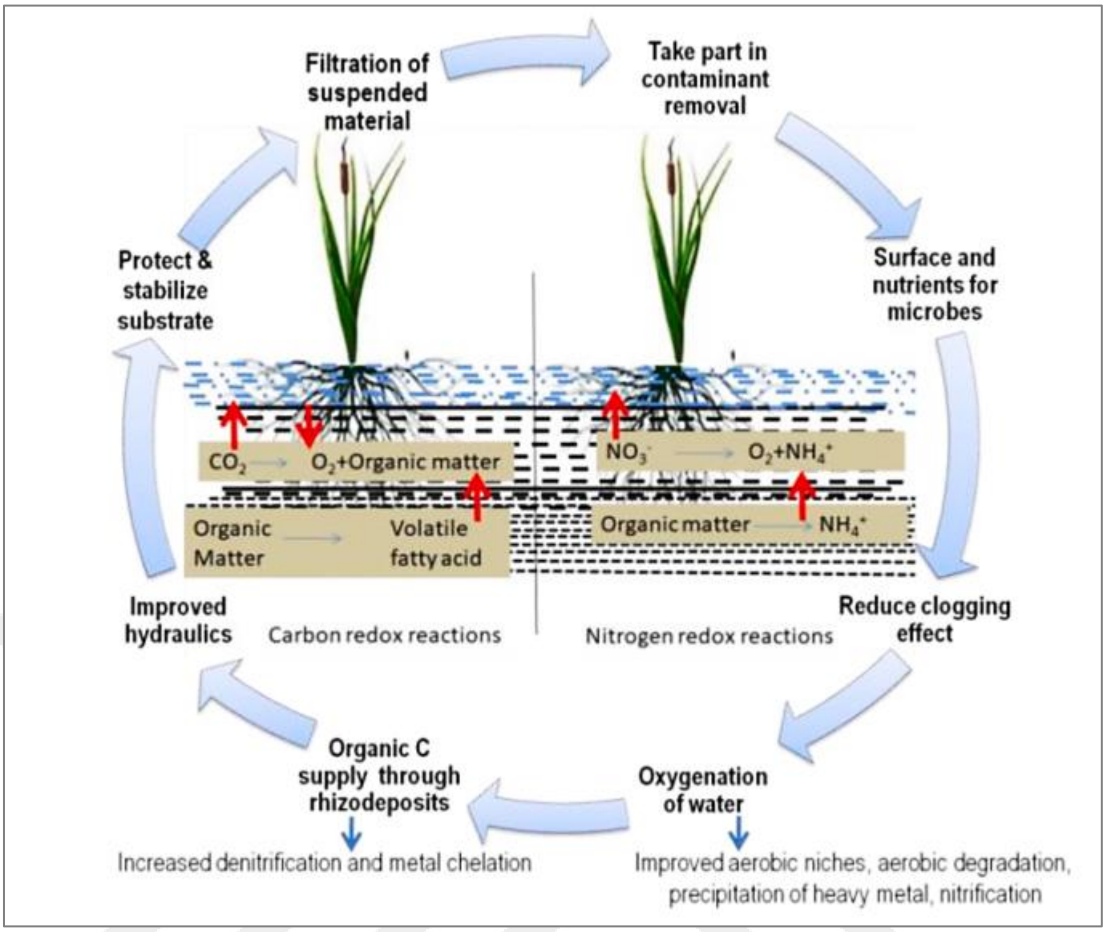


Figure 2.10: Wetland plants' functions (Kataki et al., 2021).

In these systems, where the solids in the WW are removed by sedimentation and filtration, the vegetation in the upper layer is allowed to develop deep roots, and the plants are provided to transfer oxygen to the root region. Thus, a certain amount of organic removal is encouraged in the root region (top layer of the CW). Morever, plant roots also act as a bed for microorganisms. In addition, biomass is forced to starve between pulses to control the microbial population (Varga et al., 2016; Kataki et al., 2021). Consequently, high nitrification removals can be achieved with intermittent hydraulic loading. As for denitrification, low denitrification rates can be increased by recirculating the effluent to the septic tank (Water and Sanitation Program, 2008). In addition, the denitrification process is not preferred because it limits nitrogen removal in these systems. However, a hybrid system combined with HFCW can be built to increase denitrification, but this increases initial investment costs (Al-Wahaibi et al., 2021).

2.3.1.1 Pollutant and nutrient removals

VFCW systems, which show high performance in pollutant and nutrient removal especially for domestic WW and other WW, have been proven to meet the desired removal rates for many main components such as organic matter, suspended matter and nitrogen. As the research and development phases continue, modified systems are being created for many different conditions. Therefore, there is no agreed construction model yet. Although the systems are similar in main components, they have different substrate materials, plants, operating modes and hydrological regimes for each WW and each reuse (Ilyas & Masih, 2017; A. I. Stefanakis, 2018). In VFCWs, the removal rates of the main pollutants in domestic WW treatment are listed in Table 2.2.

Table 2.2: The removal rates of parameters in VFCW (A. Stefanakis et al., 2014).

Pollutants and Nutrients	Average Removal Rates
TSS *(Total Suspended Solids)*	82% (52-99%)
BOD_5 *(Biochemical Oxygen Demand)*	85% (48-99%)
COD *(Chemical Oxygen Demand)*	75.2% (44-95%)
NH_4^+-N *(Ammonium Nitrogen)*	74.8% (33-95%)
TN *(Total Nitrogen)*	44.6% (20-94%)
TKN *(Total Kjeldahl Nitrogen)*	62.6% (45-93%)
TP *(Total Phosphate)*	62.8% (21-97%)
OP *(Ortho-phosphate)*	58.1% (26-92%)
TC *(Total Coliform)*	98.1%

In different studies for non-aerated VFCWs, the dissolved oxygen (DO) levels is very low (0.1-2.0 mg L^{-1}); however, they have obtained treatment performances of up to 90% for TSS and COD. The TSS removal was 49–90% and COD was 61-80% (Ilyas & Masih, 2017).

2.3.2 Greywater treatment in vertical subsurface flow constructed wetlands

VFCWs can easily treat lightly contaminated WW such as greywater (GW) (Nema et al., 2020). GW includes domestic WW produced by all water sources except for toilet water in residences or workplaces. GWs, other than kitchen WW, have a very low nutrient content and a nonignorable potential for pathogenicity (Boano et al., 2020). Treatment of GW, which has an easily biodegradable organic content, for reuse provides many advantages (Langergraber et al., 2019).

In the GW treatment, VFCWs, which can provide 85% removal for BOD, have high removal rates for TSS (Morandi et al., 2021). In a study comparing VFCW and HFCW system for GW treatment in CWs, it was reported that VFCWs achieved removal rates of 90-99%, 90-99% and 30% for BOD, TSS and TN, respectively (Hoffmann et al., 2011).

Although there are different approaches and views on the treatment of GW in CWs in the literature, thanks to this thesis, it is aimed to contribute to the literature by revealing experimental results on this subject and suggestions for different areas of use are presented.

2.3.2.1 Greywater characterization

GWs can be categorized according to their pollution level. While GW containing kitchen and laundry WW is defined as dark GW, light GW consists of other WWs and has low pollutant and nutrient levels (Ghaitidak & Yadav, 2013a). GW sources are categorized Figure 2.11.

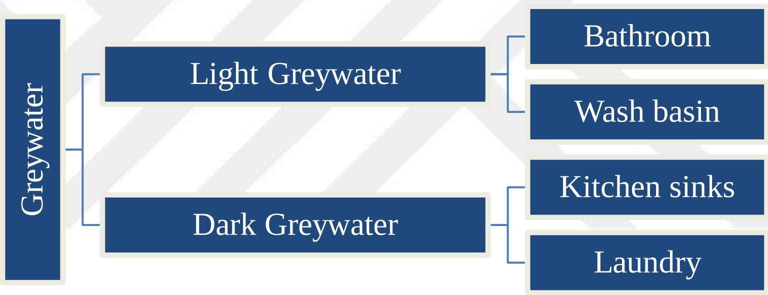


Figure 2.11: Greywater sources (Ghaitidak & Yadav, 2013a).

Light GWs can make up about 60% of the total GW. In domestic WW production, the amount of WW generated in kitchens is small. Despite this, these WWs have high content in terms of oil and OM. Therefore, it is not preferable to include these WWs in the treatment system. On the contrary, it is known that some researchers use these WWs to provide appropriate C, N and P ratios. Therefore, if the use of kitchen GWs is preferred, it may be necessary to use processes that provide advanced treatment. Due to the detergents used, especially phosphate and heavy metal content of laundry GW is high. Therefore, these less biodegradable substances may require additional modifications to the treatment system (Boyjoo et al., 2013).

The characteristic of GW depends on the behavior of the inhabitants of the source where the WW is produced, as well as the presence and consumption of water resources in that area. For GWs with highly variable organic content, the average characteristics obtained in a house are listed in Table 2.3 and the distribution of these sources is shown in Figure 2.12. And also, GW characteristics in some countries are listed in Table 2.4.

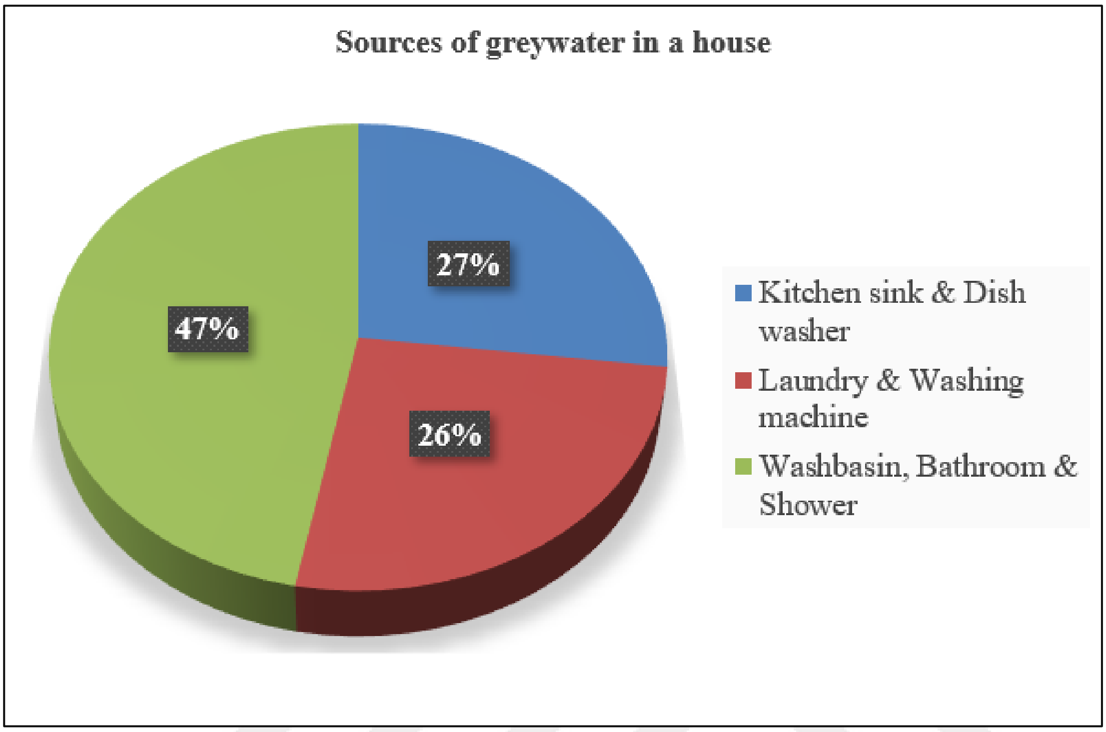


Figure 2.12: Sources of greywater in a house (Ghaitidak & Yadav, 2013a).

The physical parameters of GW include temperature, turbidity, color, suspended solids from food particles, and electrical conductivity. The range of electrical conductivity and turbidity in dark GW are, respectively, 190-3000 µS/cm, 19-444 NTU; in light GW, respectively, 14-1241 µS/ cm, 12.6-375 NTU values were measured (Üstün & Tırpancı, 2015).

The temperature of GW is often higher depending on the water source and ranges from 18-30°C. These temperatures are due to the warm waters used for cooking and personal hygiene. These temperature values are not thought to have a negative effect on biological treatment processes. Conversely, higher temperatures can lead to increased bacterial growth and precipitation in storage tanks (Üstün & Tırpancı, 2015).

Particles in water from the bathroom, laundry, and kitchen cause high TSS rates in GW. These particles also cause turbidity and clogs in the treatment processes. TSS concentration is in the range of 29-505 mg/L in dark GW and 12-315 mg/L in light GW (Üstün & Tırpancı, 2015).

Chemical parameters of GW include pH, alkalinity, salinity, dissolved organics (COD, BOD, TOC, TN, TP), heavy metals, oil and grease (O & G), surfactants and other household chemicals.

The pH value indicates whether a liquid is an acid or a base. The pH value is in the range of 6.35-10 in dark GW and in the range of 6.4-8.1 in light GW. The alkalinity value is in the range of 20–340 mg/L (Üstün & Tırpancı, 2015).

BOD and COD concentrations depend on the amount of water and products consumed. BOD and dissolved COD values range from 44–1056 and 50–2568 mg/L in dark GW, and 23–300 and 23–633 mg/L in light GW (Üstün & Tırpancı, 2015).

GW normally contains fewer nutrients compared to toilet WW. *N* level is quite low. The main source of *N* is kitchen grits. It comes from NH_3, cleaning supplies, and other products. The main source of *P* is detergents. Where *P*-free detergent is used, the average *P* concentration is in the range of 4-14 mg/L. Where detergents with the *P* are used, the concentration varies between 45-280 mg/L (Üstün & Tırpancı, 2015).

The source of O & G in GW is water from the kitchen sink and dishwasher. O & G concentrations range from 37 to 78 mg/L and 8 to 35 mg/L, respectively. High concentrations of O & G can also occur in bathrooms and laundries (Üstün & Tırpancı, 2015).

Surfactants are mainly derived from cleaning products. Concentrations vary according to the amount of detergent used. In terms of toxicity, some compounds, such as surfactants used in rinsing, can have a toxic effect on WW treatment in VFCWs. There is not enough information about the effects of surfactants found in GWs in these systems and their consequences in treatment (Eriksson et al., 2002).

Heavy metals and some nutrients have also been reported for GWs composed of many pollutants, including solids, acidic and alkaline compounds, and various oils (Rakesh et al., 2020). Moreover, along with some organic compounds such as xenebiotics (XOCs), many microbes and viruses originating from various drugs, dyes and personal products are also found in GWs (Oteng-Peprah et al., 2018).

Table 2.3: Greywater characteristics at different sources (Ghaitidak & Yadav, 2013a).

Parameters	Wash basin	Bathroom	Shower	Laundry/washing machine	Kitchen sink	Dish washer
pH	7-7.3	7.1-7.6	7.3-7.5	8.3-9.3	6.5-7.7	8.2-8.3
Turbidity (NTU)[a]	164	59.8	84.8-375	328-44	133-211	
EC (mS/m)[a]		43.7	1.4-89	2.9-703	1.4-97	90.61
TS	834	777	520-1,090	2,021-2,700	679-1,272	2,819
TSS	153-259	58-78	89-353	188-315	134-625	525
TDS			279-565	2,140-2,444	312-903	
BOD	155-205	129-173	40.2-424	44.3-462	40.8-890	470-4,450
COD	386-587	230-367	77-645	58-1,339	58-1,340	1,296
Total Alkalinity			203	333.6	205.4	
Chlorides	237	166	147-284	205-450	158-223	716
MBAS	3.3	15	14.9-61	42-118.3	41.9-59	11.1
O&G	135	77	164	181	232	328
Total N	10.4	6.6	8.7-10.92	14.28	6.44-6.44	
Total P			1.12	51.58	0.69	
TC (MPN)[a]	9.42E3	6,350-5.1E6	2E2-6.8E3	2E2-4.2E6	2E2-5.29E2	4.30E6
FC (MPN)[a]	3.50E4	1.5E5-4E6	64-4.0E6	13-4.E6	200.5-1.2E6	6.0E4-3.2E5
E. coli (MPN)[a]	10	82.7	2E2-1.49E3		2E2	
Boron (B)	0.44	0.41	0.35-0.35	0.4	0.02-0.02	3.8
Calcium (Ca)			15.7-59.9	18.7-24	19.69-23.6	
Magnesium (Mg)			23-56.1	15.1-60.8	16.6-21	
Sodium (Na)	131	112	109.5-184.5	302.1-667	70.1-148.9	641
Arsenic (As)			0.03		0.015	
Copper (Cu)			0.01-0.0127	0.0064-0.01		
Lead (Pb)			0.1036	0.0829	0.0622	
Nickel (Ni)			0.035	0.0352-0.12	0.0352-0.04	
Zinc (Zn)			2.4	0.14	0.039-0.04	

[a] : Units in brackett; all other units are in mg/L

Table 2.4: Greywater characteristics in some countries (Boyjoo et al., 2013; Ghaitidak & Yadav, 2013a).

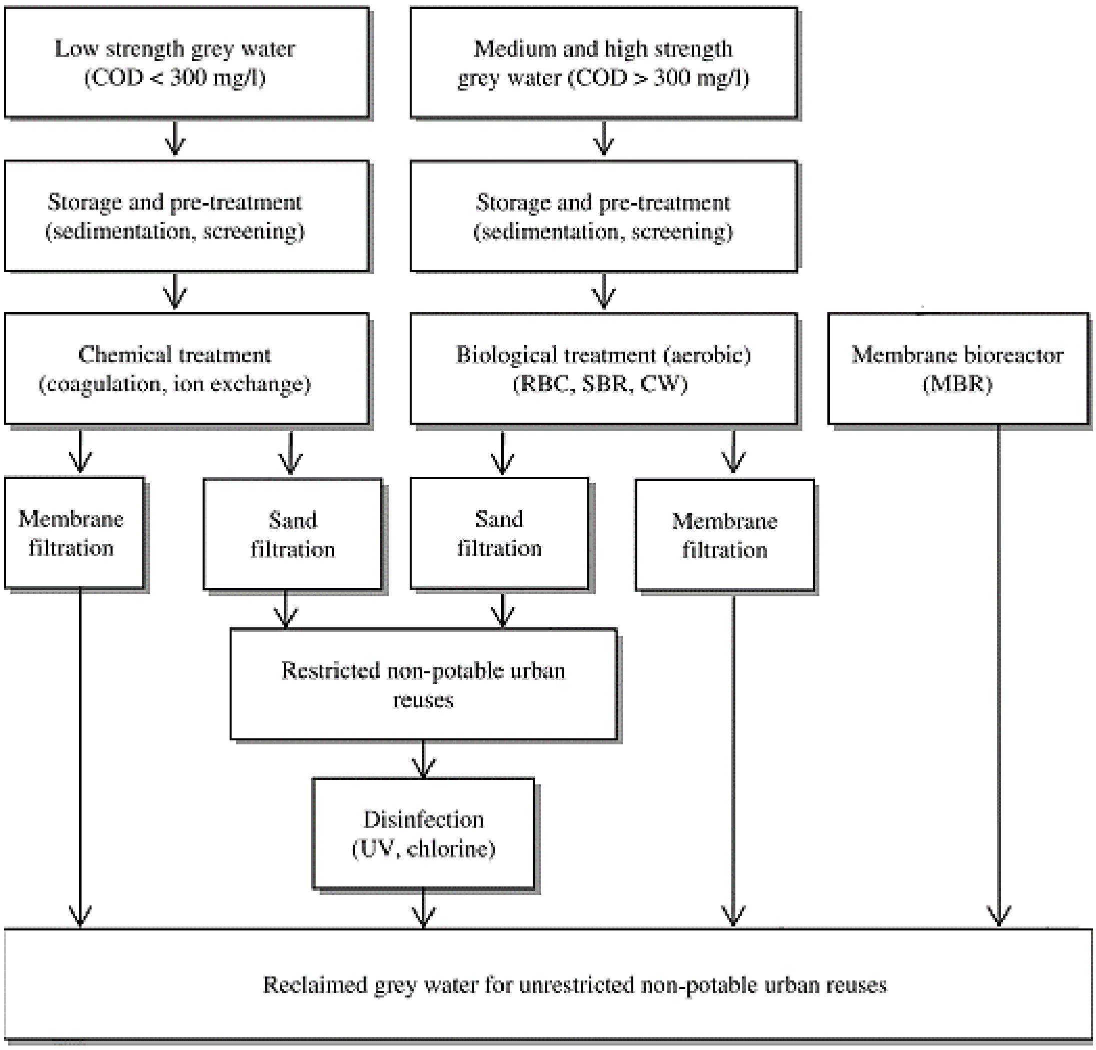
Parameters	India	Israel	Jordan	Oman	Sweden	Taiwan	Türkiye	UK	USA
pH	7.3-8.1	6.3-8.2	6.4-9	6.7-8.5	7.8	6.5-7.5	7.1-7.2	6.6-7.6	6.4
Turbidity (NTU)[a]		23-35	49	12-444		43		26.5-164	31.1
EC (mS/m)[a]		120-170	89-703	1.4-24	196		401-495	32.7	23
TS	497	777-2,819	659-2,653	520-2,700		405	48-54		
TSS	100-283	30-298	94-845	11-505		29	54	37-153	17
TDS	573	599	565-2,444	119-2,385					171
BOD	100-188	74-890	36-942	25-262	425	23	91	39-155	86
COD	250-375	840-1,340	58-1,712	58-486	890	55	190-350	96-587	
TOC		91-582		63-175	304		92	60-99	43
Chlorides	53	166-716	147-205			206			
MBAS		3.3-61	39	3-118	30				
O&G	7	77-328							
Nitrate	0.67	0.7-3.5	0.68	8-29			1.30	3.9	
Total N		10-34.3	6.44-52		75		7.60	4.6-10.4	13.5
Total P	0.012	1.9-48	0.69-51.58		4.2		7.2	0.4-0.9	4
TC (MPN)[a]			2.5E2-1E7	2E2-3.5E3		5.1E3	1.1E4	6.4E3-2.2E7	
FC (MPN)[a]		3.5E4-4E6	13-3E5	2E2	1.7E5		1.10E4		
E. coli (MPN)[a]		5E4	2E5	2E2				10-3.9E5	5.4E2
Ca	0.13	79.6	24-60	15.7-19.7					
Mg	0.11	47.6	15.1-23	21-61					
Na	32-50	89-641	70-302	149-667					

[a] : Units in brackett; all other units are in mg/L

2.3.2.2 Greywater treatment proccesses

Physical, chemical or biological treatment technologies are used in GW treatment to reach the desired standards depending on the characteristics of the water. Constructed wetland (CW), rotary biological reactor (RBC), sequential batch reactor (SBR), membrane bioreactor (MBR) technologies are used in the biological treatment of GW. Electrocoagulation (EC) and ion exchange ara used in the chemical treatment of GW. In order to provide GW recovery standards in other biological processes other than the membrane bioreactor, filtration or precipitation is the pre-treatment, and disinfection with UV or chlorine as the final treatment (Üstün & Tırpancı, 2015).

Table 2.5: Recycling of the low, medium and dark greywaters (Li et al., 2009).



2.3.2.3 Greywater reuse

Fresh water resources have reached the stage of depletion due to population growth and changing lifestyles depending on industrialization. Therefore, nations have made every effort to protect water resources. Aside from the WW originating from the industries, significant amounts of WW are also generated from the cities. For this reason, sustainable management of WW is essential in cities as well as in industry. One of the options for realizing sustainable WW management and reducing the demand for water is the reuse of treated water (Al-Jasser, 2011; Madungwe & Sakuringwa, 2007; Shamabadi et al., 2015). Due to the characterization of the GWs, its easier treatment compared to other WWs has made them an attractive option, especially for non-potable reuses .

GWs, which are composed of other domestic WW sources other than toilets, constitute 50-80% of domestic WW production (Penn et al., 2012). They can be a very important resource, especially for countries under water stress. And with the use of this precious resource, they can meet the demand for many non-potable uses. Moreover, the pressure on WW treatment plants is reduced, resulting in many direct and indirect benefits (Shaikh et al., 2019). Figure 2.13 shows the GW generation for countries by income level (low-income and high-income).

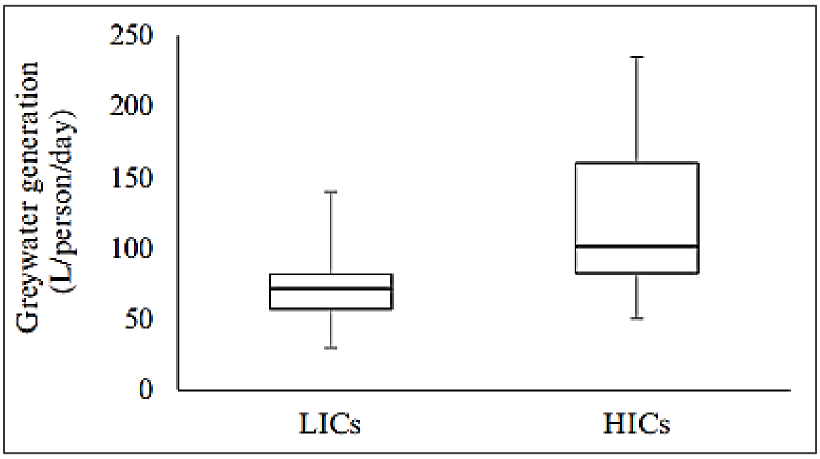


Figure 2.13: The GW generation for countries by income level (Shaikh et al., 2019).

The suitability of the treatment of GW in decentralized treatment systems has also increased the interest of governments in the management of these resources. On-site treatment and reuse of GW has become an attractive option, especially for densely populated buildings. As the reuse of GWs have become widespread in recent decades, their large-scale application is scarce (Shaikh et al., 2019). Besides, researches have been carried out for the treatment and reuse of GWs in recent years. Some countries have presented and implemented their regulations for the reuse of these WWs, which can be used as inlet water in many treatment systems depending on the end-use purpose (Batisha, 2020). Additionally, most parameters used for WW are also used for GW reuse (Al-Jasser, 2011).

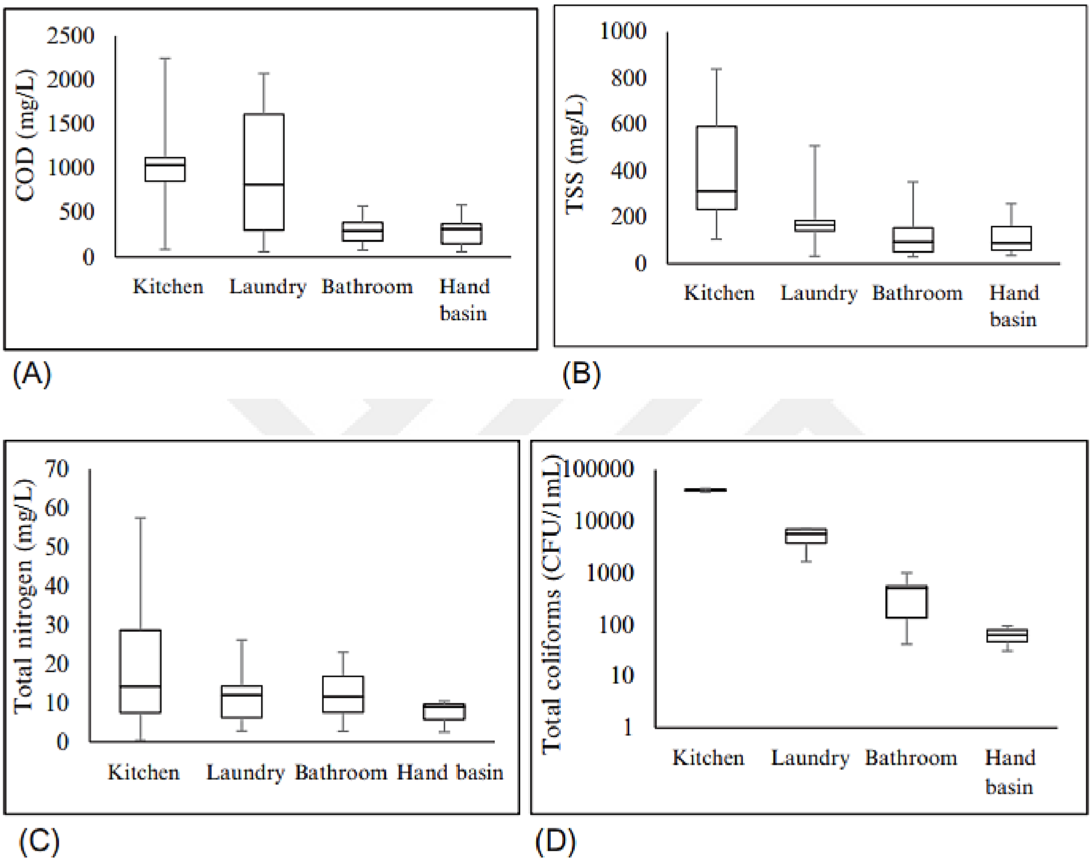


Figure 2.14: Source-based characteristics of GW (Shaikh et al., 2019).

A) COD, B) TSS, C) TN, D) TC

After the GWs are treated, they can be used for garden irrigation or as toilet flushing water. However, there are several difficulties associated with these uses. Because existing building installations need to be renewed and this GW must be stored depending on the amount of use. Especially when it comes to the reuse of GW in new housing and building designs, designing the installations accordingly will eliminate these difficulties. Planning is also essential for landscaping and garden irrigation purposes. Due to the possibility of irrigation to pollute the groundwater, GW needs to be treated at levels that will not harm the environment and human health (Üstün & Tırpancı, 2015). The reuse fields of GW are listed in Figure 2.15.

Figure 2.15: The reuse fields of greywater (Kutlu et al., 2017).

Water consumption varies depending on the living standard of the users. It is accepted that 25% of the water consumed in residences and living spaces in Europe is used for toilet flushing, 5% for cleaning, 5% for irrigation and 13% for laundry. Therefore, by using treated GW instead of drinking water in such uses in order to protect scarce fresh water resources, nearly 50% water savings are achieved.

Instead of using high quality drinking water as drinking water, the amount of drinking water usage is reduced by using treated GW that is not of drinking water quality, thus helping to protect natural water resources. Since the amount of treated GW at the source and WW discharged to the sewerage will decrease, the volume of treatment plants built by local governments will decrease and investment costs will decrease. As GW recovery systems reduce drinking water usage rates, they will also reduce mains water distribution costs. GW is a valuable source of water for garden irrigation and growing plants, especially in arid regions. When GW is used as irrigation water, it is also a good source of fertilizer and nutritive water (Kılıç, 2022).

Untreated GW should not be stored or stored. The untreated GW starts to stink in a short time and causes disease-causing microbes to form.

The use of treated GW as reusable water is not harmful in terms of health. Currently, many countries in the world have accelerated the enactment of regulations and laws on this issue in order to ensure the reuse of the treated GW. In practice, it has been proven that the probability of posing a health risk from the reuse of GW is very low. However, since GW may contain pathogenic microbes that cause disease, it is imperative that appropriate treatment systems are installed and regularly maintained (Kılıç, 2022).

The precautions to be taken to prevent the health risk that may arise from the reuse of GW are listed below. Mains water and treated GW installation should be made in accordance with the DIN 1717 standard and these water systems should intersect and it should be ensured that there is no connection between them. In order to achieve this, mains water and treated GW installations should be clearly identified by using pipes of different colors or by labeling, ensuring that there is no intersection (Kılıç, 2022).

- Treatment of all GW resources should not be preferred too much. Initial investment and operating costs can be reduced by treating only the amount of GW that will meet the domestic water requirement. For this reason, lightly polluted GW sources such as showers, sinks and bathtubs should be purified and the treated water should be reused in toilet reservoirs and laundry washing.
- When used as irrigation water, it must be checked regularly that the DIN 19650 irrigation water hygiene conditions are met, and by attaching labels to the faucets connected to the GW system in the garden, drinking or contact with the body should be prevented.
- The amount of GW does not depend on external factors, that is, regardless of the weather conditions, GW is constantly produced due to personal hygiene needs.
- The pollution level of GW basically determines the habits of the consumers. The resulting contamination is the result of personal hygiene products, detergents, soiled clothing and body dirt used. These pollutants are easily classified as biodegradable. Due to this easy biodegradation, if the GW is not treated immediately, the degradation process will continue with sulfates, resulting in unpleasant odours. Therefore, untreated GW should not be stored or stored.

Particular attention should be paid to the following issues in GW installations (Kılıç, 2022):

- Mains and domestic water lines must not be connected to each other in any way. The mains water supply line to the system should be made as free flow from a certain distance in accordance with the DIN EN 1717 standard and should not allow back flow.

- There should be a ventilation line to prevent odors that may occur in the tanks used in the GW recovery system. If possible, the ventilation line should be brought up to the roof separately from the house's drainage line ventilation.

The treatment of GW is carried out faster, in a shorter time and at less cost compared to other domestic waters. The reuse of treated GW not only contributes to the protection of water resources, but also has a positive effect on the water balance in nature. The benefits of GW recovery are summarized below (Tanık et al., 2016):

- Reducing water use by up to 50%,
- Reducing the use of (mains) drinking water as utility water,
- More efficient use of natural water resources,
- Decreased demand intensity in mains water distribution lines,
- Being a resource for garden irrigation and growing plants, especially in arid regions,
- Much faster and easier purification than black water,
- The water obtained must be of a quality that will provide hygienic conditions

The disadvantages of GW reuse may include (Ibrahim et al., 2014):

- Additional cost in installing and maintaining of the GW system,
- Systems require a level of control, and also maintenance,
- Suitable equipments to prevent the health and environmental risk due to pollution risk

2.3.2.4 Greywater reuse in Türkiye

The GW produced in the bathroom has been directly used for garden irrigation since ancient times. In Israel, it has been reported that GW is used for irrigation of fruit trees. However, it is highly recommended to treat GW before use. The direct long-term use of GW for irrigation causes the accumulation of materials in the water. In this context, it affects plant health and soil structure negatively and as a result causes groundwater pollution. The use of untreated GW in toilet flushing can cause staining problems in the bowl. As a result, other problems may arise from the use of more cleaning chemicals (Üstün & Tırpancı, 2015).

According to Istanbul Water and Sewerage Administration (İSKİ) data, the daily water consumption of a core family of 4 is 480 liters on average. In rural areas, the amount of water consumption is very low, such as 55 – 60 liters per person.

Turkey is among the countries that will potentially face water scarcity. Therefore, reuse policies and sustainable solutions need to be implemented. The reuse of GW and harvesting of rainwater have come to the fore, and these issues have begun to take place in various action plans. According to the "Urban Infrastructure Goals" announced in the Eleventh Development Plan (2019-2023), it is aimed to increase the "Reuse Rate of Treated WWs" from 1.2% in 2018 to 10% in 2023. Among the policies included in the "National Water Plan (2019-2023)" published by the Ministry of Agriculture and Forestry, there is an article "GW use and rainwater harvesting technologies should be encouraged". When evaluated in Istanbul, the İSKİ has introduced a GW project for buildings with a total construction area of over 30,000 m^2 and storm water harvesting project approval for parcels over a thousand square meters, as of March 1, 2021. In accordance with the legal regulations, these obligations have to be implemented in the field, but the applications are not widely known on how to make the practical application (Çetinkaya, 2022).

The projects of a company, which is one of the first companies in Turkey operating in the field of sustainability management, on these issues were examined. It has been determined that only two projects out of 136 certified projects have been working on GW reuse. In five projects, it was reported that studies were carried out on the reuse of GW together with rain water. Studies have been carried out on the reuse of rain water, and there is a need for progress on the reuse of GW. It is aimed to create an encouraging effect by examining these issues and creating informative documentation. When the projects are examined in terms of reuse, the use for landscape purposes and use for reservoir purposes come to the fore in general. It is necessary to increase the usage purposes by obtaining higher treatment efficiencies (Çetinkaya, 2022).

The reuse rate of treated WW in some countries has reached 80%. Therefore, the reuse of GW treated is also of great importance for Türkiye. It is also important to meet the water quality criteria in the reuse of treated WW (Tanık et al., 2016).

In Turkey, GW recycling systems have gained importance in recent years and are being implemented in various new projects. Examples of these projects are the Zincirlikuyu Zorlu Center, Varyap Meridian, and Levent Özdilek Projects in Istanbul. The first 5-star hotel GW recycling project with a subsurface membrane system in our country belongs to the Istanbul Hilton Hotel. The recycled GW is used in garden irrigation and toilet reservoirs (Tanık et al., 2016).

Within the scope of this thesis, the GW of this hotel was used as WW in the wetland system established in the laboratory

2.3.2.5 Greywater reuse standards

There is no internationally accepted regulation for treated GWs. Although there is no such regulation, many countries have established their own guidelines for GW reuse. However, there are differences between these standards. For some countries these standards are listed. On the other hand, the risk situations associated with these regulations are unclear. Moreover, its risk levels in terms of public health have not yet been determined. It should not be overlooked that there is a need for studies on this situation (Shaikh et al., 2019).

The water quality criteria valid in Germany for the use of GW in toilet reservoirs and laundries after treatment have been announced by the Berlin Senate Office and are shown in Table 2.6. Total coliform and *E. coli* values, which are microbiological parameters, are accepted as Swimming Water Quality Values (76/160/EEC) in EU standards (Üstün & Tirpanci, 2015).

Table 2.6: Quality requirements for toilet flushing (Üstün & Tirpanci, 2015).

Parameter	Values
BOD_7	<50 mg/L
Oxygen Saturation	>50%
Total Coliform[a]	<100/mL
Fecal Coliform[a] (*E. coli*)	<10/mL
Pseudomonas aeriginosa[b]	<1/mL

[a] : Conforms with EU 76/160/EEC directive
[b] : Conforms to German drinking water standards

The recommended domestic water quality conditions for washing laundry are given in Table 2.6. As a result of scientific research on the laundry washed with treated GW and mains water with the values in Table 2.6, it has been revealed that there is no sanitary difference between the laundry washed with mains water and treated GW, even after drying (Üstün & Tirpanci, 2015).

The water values required for irrigation water are regulated by DIN 19650 standards (The German Institute For Standardisation). These quality standards relate to the sanitary and microbiological aspects of water used in agriculture, horticulture, parks and sports facilities (Üstün & Tirpanci, 2015).

Practices regarding the reuse of treated WW in our country are evaluated within the scope of the Environmental Law No. 2872, which was published in the Official Gazette dated 11.08.1983 and numbered 18132. These reuse practices are based on the Water Pollution Control Regulation, which came into force by being published in the Official Gazette dated 31.12.2004 and numbered 25687, and the "Urban WW Treatment Regulation", which entered into force after being published in the Official Gazette dated 08.01.2006 and numbered 26047. It is applied within the framework of the "Communiqué on WW Treatment Plants Technical Procedures" (Saraoğlu, 2014).

In the 28th article titled “Use of Treated WW in Irrigation” of the Fifth Chapter of the Water Pollution Control Regulation titled “Principles of Discharge of WWs”, “In regions where irrigation water is scarce and has economic value, the use of treated WW, which meets the irrigation water quality criteria given in the Technical Procedures Communiqué of the Regulation on Water Pollution Control, is encouraged as irrigation water. For this purpose, the pre-processes to be applied and the necessary examinations are made in accordance with the Technical Procedures Communiqué. The suitability of a WW for such uses is determined by a commission to be formed by the governorship from the provincial directorate of environment and forestry, the provincial directorate of agriculture and the regional directorate of state water works.” statement is included (Saraoğlu, 2014).

In subparagraph (e) of Article 5 of the Second Part of the Urban WW Treatment Regulation, titled "Principles and Principles", one of the principles envisaged for the implementation of the regulation is "Treated WW can be reused under appropriate conditions. Disposal methods are determined to minimize the negative effects on the environment. The reuse of treated WW is subject to the provisions of Article 28 of the Water Pollution Control Regulation published in the Official Gazette dated 31/12/2004 and numbered 25687.” specified as (Saraoğlu, 2014).

3. MATERIALS AND METHODS

GW samples were taken periodically from a large-scale hotel in Taksim, Istanbul, of a worldwide hotel chain, where the GW is collected with separate installations. The characterization studies of the raw GW collected and brought to the laboratory by fulfilling the sampling and storage conditions were carried out. Within the scope of characterization studies, COD, TN, NH_4-N, NO_3-N, NO_2-N, TP, DO, turbidity, pH and temperature were measured. The hotel in Istanbul where GW samples were taken and its GW treatment plants are shown in Figure 3.1.

Figure 3.1: The hotel in Istanbul where GW samples were taken and its GW treatment system (MBR Arıtma, 2011; Wikipedia, 2022).

3.1 Lab-Scale Design of Vertical Subsurface Flow Constructed Wetland

In the Soil Laboratory in the Environmental Engineering Building of Istanbul Technical University, a solid plastic transport box, approximately 70 × 40 × 60 (h × w × l; cm), used for transporting materials in industries, was used as a reactor for GW treatment. The plastic carrying case used as the VFCW and its sizes are shown in Figure 3.2.

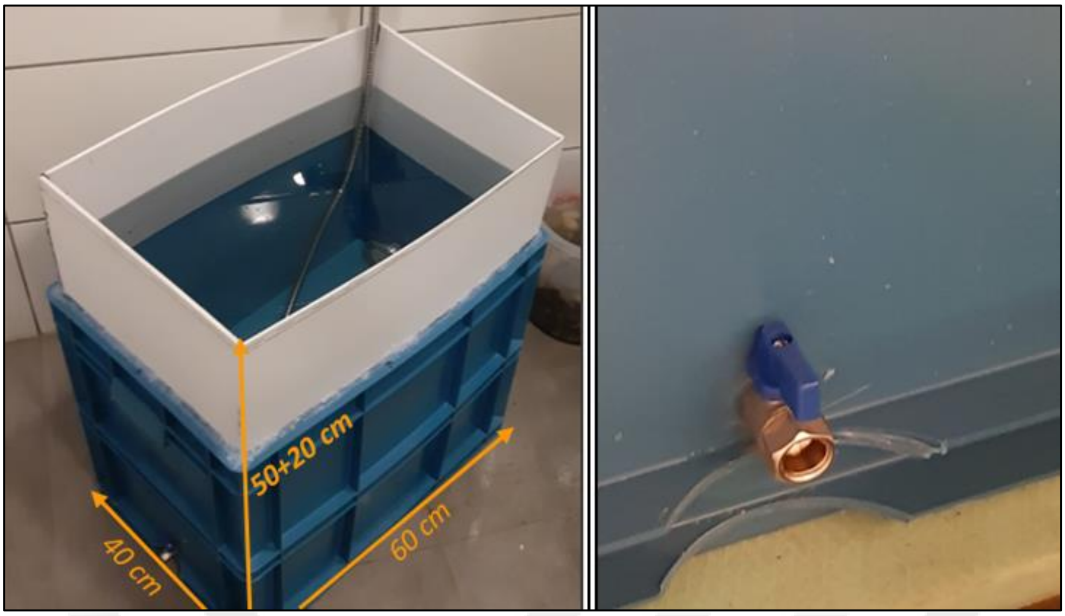


Figure 3.2: The plastic carrying case used as the VFCW and its pneumatic tap.

3.1.1 Substrate choice and placement

Sand and pebble stones, which are widely used in all CW types, were preferred in the selection of filter material. Materials naturally found in and extracted from river beds due to transport and erosion were purchased first-hand. The filter materials preferred are shown in Figure 3.3.

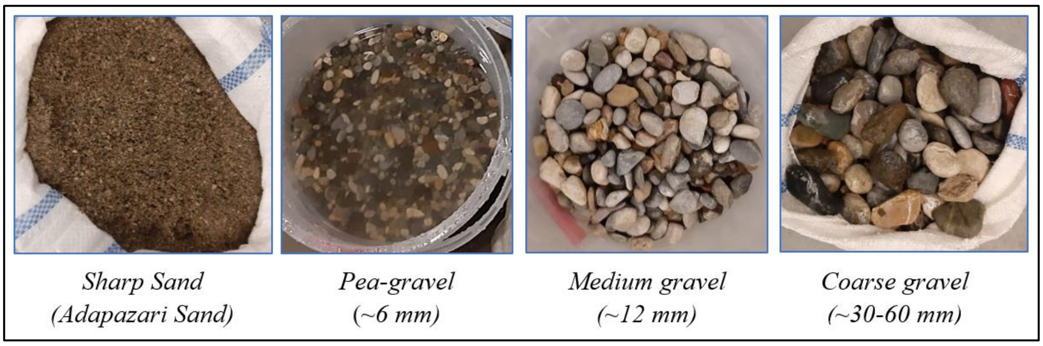


Figure 3.3: The filter materials preferred for VFCW reactor.

Materials that act as filters and media in the wetland reactor were added to the bed according to the general design criteria (Wallace, 2006). Any perforated and solid pipe that will provide oxygen transfer from the atmosphere is not included in the system. Before these additions were made, 130 L of water was added to the reactor and the pressure and tightness conditions were tested and no adverse events were observed. The treated GW was taken from the sealed pneumatic tap located close to the bottom layer (5 cm above the bottom layer). The media material profile based on the design criteria is shown in Figure 3.4.

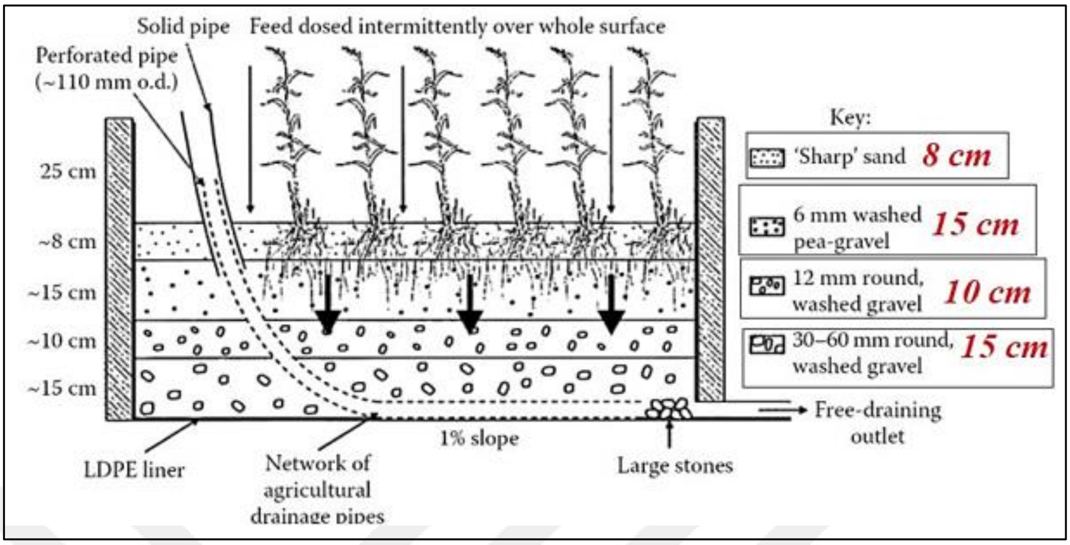


Figure 3.4: The media material profile based on the design criteria (Wallace, 2006).

Washed round stream gravels in the range of 30-60 mm were placed on the bottom floor of the reactor, which is located on the lower floor of the wheel conveyor with LED fluorescent lamps, which illuminate the plants in the system for 12 hours a day, to provide a height of 15 cm. The conveyor is shown in Figure 3.5.

Figure 3.5: The conveyor with LED fluorescent lamp.

While placing the gravels, the largest gravels were placed around the outlet line so that there are no blockages at the drainage stage. Stream gravel (12-22 mm, No. 2), which did not pass through a approximately 12 mm sieve, was placed on the coarse gravels placed on the bottom layer of the VFCW reactor, providing a height of 10 cm. Afterwards, the smallest number (<11 mm, average 6 mm) stream gravel was placed to provide a height of 15 cm. Sand was added to the pebbles, which formed approximately 38-40 cm in height, to provide a height of 8-10 cm. After that, the pipes providing dripping GW inlet to the system were laid. The incrementally process of laying the substrate on the wetland bed and piping is shown in Figure 3.6. After this process, macrophytes, which are a component of VFCW systems, were planted.

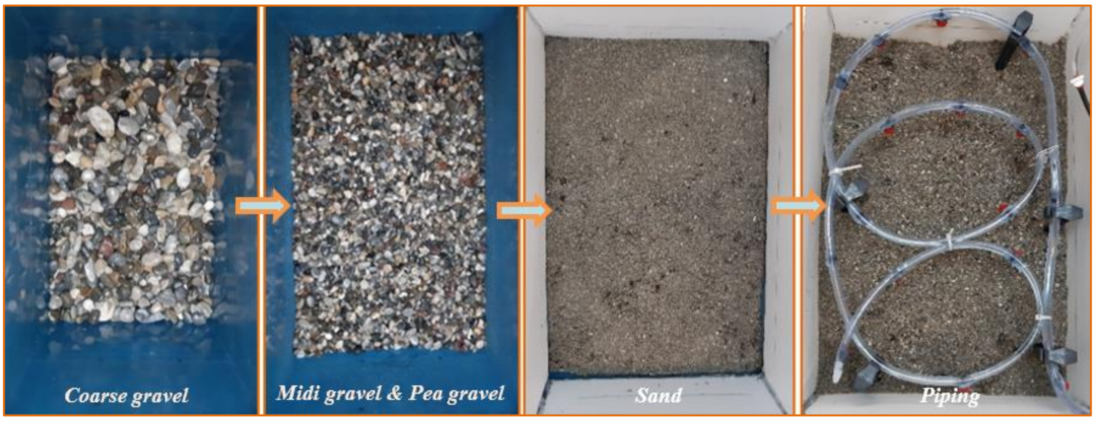


Figure 3.6: The incrementally process of laying the substrate on the wetland bed and piping.

3.1.2 Macrophyte choice and planting

Cyperus alternifolius plant was preferred as a component of the VFCW system in the treatment of hotel GW. There are many types of plants that can be used in wetland systems; however, since it is recommended to choose locally available plant species and it is a plant that can be grown in Türkiye, these macrophytes were planted. This plant, which is also called "Japon şemsiyesi (Japanese umbrella)" or "şemsiye palmiyesi (umbrella palm)" in Turkish, is frequently preferred as an ornamental plant, and this choice has also been effective. Moreover, the number of studies on the use of these plants in treatment wetlands is quite low. In these studies, it has been reported that these plants affect the treatment efficiency.It seems that during the initial growing periods, plant species have a high taking capacity. The parallel observation achieved a TP uptake of 17% by C. alternifolius in VFCWs that were harvested. It has been reported that there is improvement in TN and TP removals in the VFCW reactor planted with *C. alternifolius* plant. The water loss ratios owing to evapotranspiration (ET) for vertical flow CWs treating WW equivalent to 20 mm/d for *T. angustifolia*, 11.9 mm/d for *C. alternifolius*, and 7.9 mm/d for the unplanted VFCW (A. Stefanakis et al., 2014). However, data on its use in the CWs, especially the VFCWs, are scarce. This reason has also been effective in the selection of macrophytes. The *C. alternifolius* is shown in Figure 3.7.

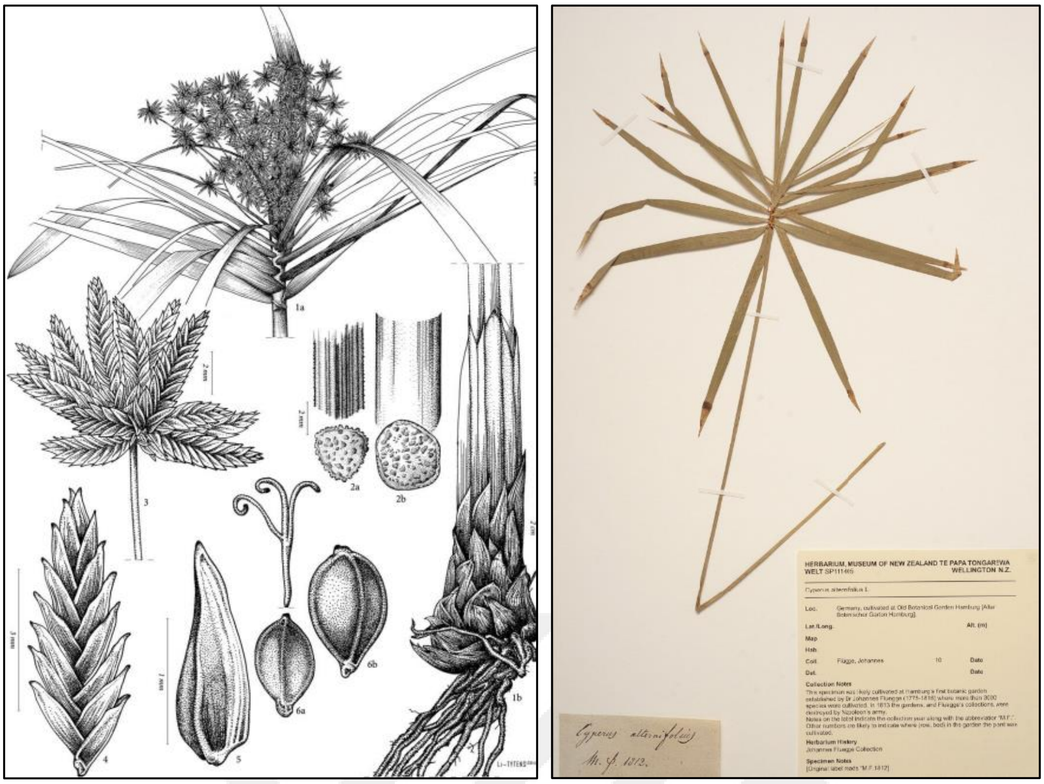


Figure 3.7: *Cyperus alternifolius*’ organs and its an example (Flügge, 1865; Verloove, 2014).

1a-1b: habit, 2a: rhachis part, 3: spike, 4: spikelet, 5: glume, 6a: nutlet & style

The *C. alternifolius* is 50 to 100 cm long and reaches almost half a meter wide. It is rhizomatous. The body is triangular, hard and hairless. Their leaves at the base are very short. At the apex there are about 30 linear leaves, which can grow up to 30 cm. The leaves are hairless, parallel-veined and fine-tipped. The inflorescence is a large umbrella, with 10 to 20 arms, and the spikelets are greenish-brown. It has been reported that this Madagascar origin plant, which blooms in the June-August period, spreads along the sea coasts of Türkiye due to its spread as an ornamental plant. The *C. alternifolius*, naturalized on the Izmit coast in Kocaeli, is shown in Figure 3.8.

Figure 3.8: The *C. alternifolius*, naturalized plant on the Izmit coast (Doğan, 2020).

Since it does not have a very widespread natural spread in the Türkiye, a *C. alternifolius* pot with new roots and young leaves, in Figure 3.9, was obtained from Istanbul's largest nursery (Büyük Çamlıca Plant Nursery). The Japanese umbrella supplied has been separated almost completely from the soil where it is grown and its roots are washed. Afterwards, it was divided into 3-4 parts and planted in the upper layer of the sand layer, which is in the top layer of the substrate material in the reactor. Finally, the system was made ready for the acclimation process.

Figure 3.9: The Japanese umbrella pot supplied and its planting to VFCW reactor.

3.1.3 Hydraulic conditions

The VFCW reactor was fed with GW for 4 h per pulse until it gets saturated. The GW holding volume of the reactor was 22.5 L. The feed mode was operated with a hydraulic loading rate (HLR) of 204 mm d^{-1}, a specific pulse volume (SPV) of 102 L m^{-2}, and a specific hydraulic loading rate (SHLR) of 0.45 L m^{-2} min^{-1}.

3.1.4 Feeding mode and sampling

The VFCW system installed in the laboratory was operated in batch feed mode. The intermittent feeding strategy is a very common feeding mode in vertical flow wetlands. They do not need ventilation with any mechanical equipment. Because there is a time interval between pulses, opportunities for oxygen entry into the system occur. Thus, by providing oxygen to the system, an aerobic environment is created and the necessary oxygen for the OM oxidation is in the VFCW reactor.

Dosing was carried out twice a day according to the experimental plan and designed hydraulic conditions. The GW, which enters the system as dripping, is kept in the system during feeding. That is, the exit valve of the reactor is kept closed during the feeding phase. As soon as a beat is completed, output from the system is started. The output flow is equivalent to the input flow. Thus, the first drop and the last drop of water entering the system were kept in the system for the same time. Following the feed mode, the VFCW reactor was slowly emptied and the system entered in the rest mode for 8 hours. This cycle was repeated two times per day. Samples were taken at the end of the feed mode (fully saturated state) and during the rest mode (unsaturated state) to determine removal efficiencies.The feed mode of the VFCW reactor is represented in Figure 3.10.

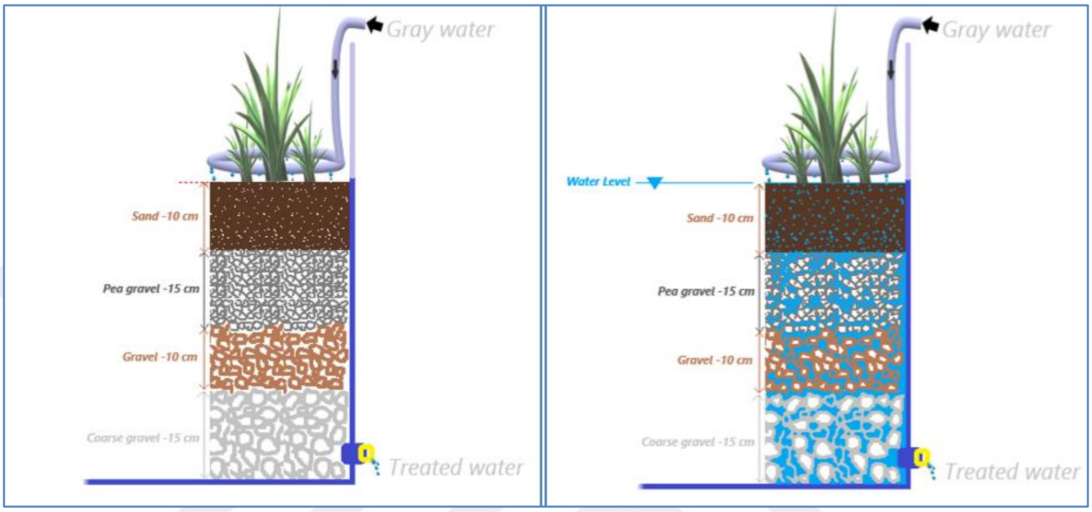


Figure 3.10: The feed mode of the VFCW reactor.

3.2 Preparing the VFCW Reactor for Operation

The system, which was established in March 2022, was put into operation and followed up in April and May with mains water (not distilled or feed water) with 12 hours of daily lighting at normal temperatures to observe the adaptation of plants and the growth of fresh roots. The acclimation period was determined as 2 months. During this process, the alteration in the outer view of the plants was monitored in a controlled manner.

In the first stage, the system was fed with mains water at different feeding modes and retention times (free drainage and partial saturation) in order to ensure the removal of inorganics and OM that may arise from the washed filter materials and root-soil components of the plant from the system, and to observe the appropriate color/turbidity conditions. This process was continued until stable color/turbidity conditions were achieved. In the figure, the effluent that partially met the appropriate conditions for color/turbidity is seen in the left balloon flask in Figure 3.11, and the turbid water taken in the stages until it reaches the left output is seen in the right flask.

Figure 3.11: The change in the color/turbidity states during the process of passing water through the system.

As of June, it was observed that the plants adapted to the system and laboratory conditions and there were no adverse events.

3.3 Operation of the VFCW Reactor

The raw GW of the international hotel in Istanbul, where the GW is collected separately and treated and recovered with a membrane bioreactor (MBR), was collected for certain periods according to the operating conditions and test periods. The flow chart of the hotel's GW recycling plant is shown in Figure 3.12.

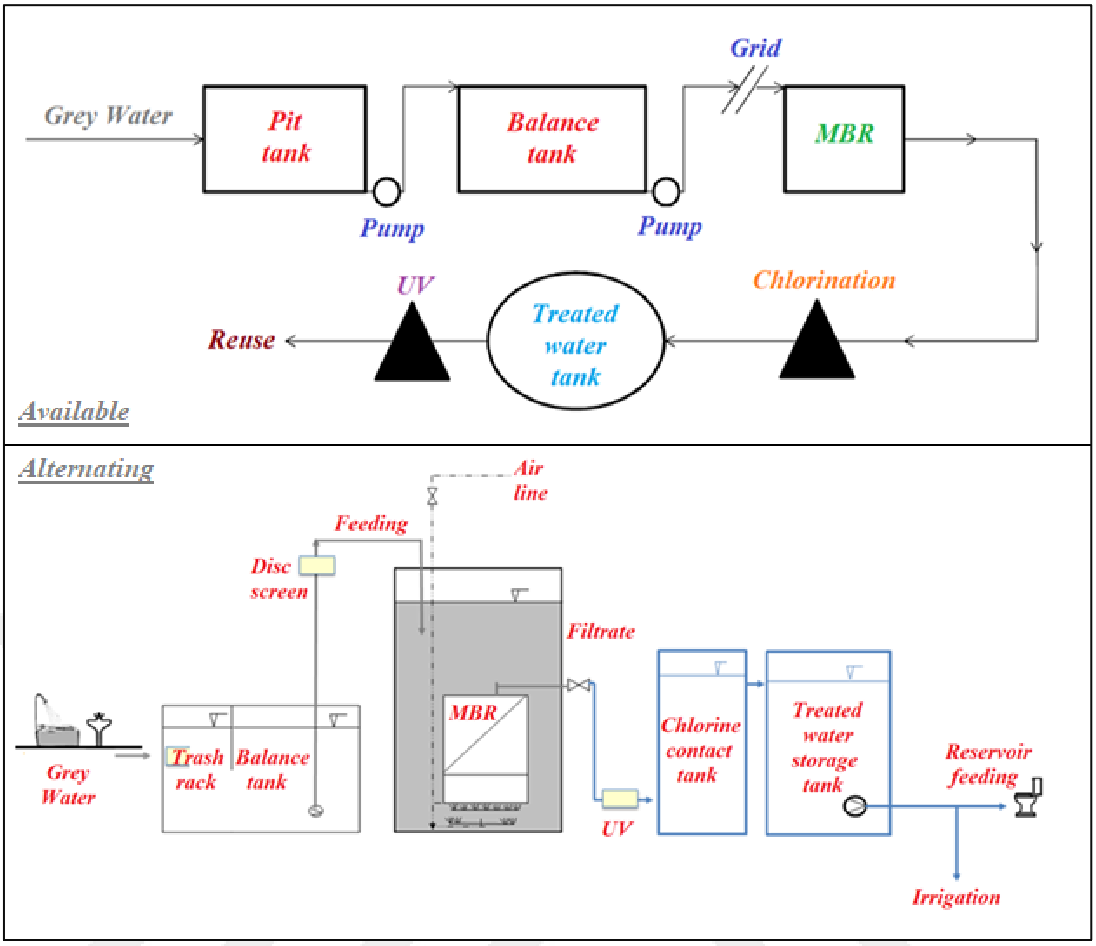


Figure 3.12: The flow chart of the hotel's available and alternating GW treatment and recycling plant (TÜBİTAK, 2015).

Since the characterization data of GW was reported both in the report published by TÜBİTAK and in the thesis on GW made in 2015, comparisons were made with the data of the characterization study conducted within the scope of this thesis and the consistency of the data was checked. The characterization study and comparison plot are shown in the next section.

The system was fed with gray water for 2 weeks before the main experiment plan was carried out. Thus, biofilm growth was provided for the activity of microorganisms.

The GW was transferred from the feeding tank to the system with an aquarium air pump. The effluent is provided by gravity. The WW entering the system by dripping slowly drains and saturates the system in a certain period of time. OLR, HLR, SPV, SHLR rates have been calculated depending on the flowrate adjustment of the system that is ready for operation. According to the results of the calculations, the system was operated with total 2 cycles for 4 days, with the principle of fill-contact-draw-rest, in order to adapt the system to raw GW and to increase its microbial activities, the operating conditions of which were determined. During this process, processes such as flow adjustment and hydraulic conditions of the system were followed. And the system has been made ready for operation by making appropriate adjustments.

3.4 Analyzed Parameters

The water quality of GWs can be determined by analyzing various physico-chemical parameters and nutrients. In this part, the parameters analyzed in ITU and DSI laboratories are described. Measurements of standard parameters such as TSS and COD were made in accordance with APHA standards, by applying the specified methods. TN and TP measurements were measured using proven consistency kits. In the light of the information obtained from the literature about GW characterization, the measuring ranges of the kits used were selected. On the other hand, various N parameters (ammonia-N (NH_4-N), nitrite-N (NO_2-N) and nitrate-N (NO_3-N)) are analyzed standard method. The parameters measured in lab-scale studies and the measurement frequency are given in Table 3.1 below.

Table 3.1: The parameters measured in lab-scale studies.

Parameter	Frequency	Method
pH	2-4/cycle	TS EN ISO 10523
T (°C)	2-4/cycle	TS EN ISO 10523
DO	2-4/cycle	TS EN ISO 5814
TSS	2/week	APHA, 2017
COD	2-4/cycle	Kit and APHA, 2017
TN	2-4/cycle	Kit and APHA, 2017
NH_4-N	2-4/cycle	TS EN ISO 14911
NO_3-N	2-4/cycle	TS EN ISO 10304-1
NO_2-N	1/cycle	TS EN ISO 10304-1
TP	2-4/cycle	Kit and APHA, 2017

3.4.1 pH

pH was analyzed in accordance with standards and guidelines. Thermo Fisher Scientific brand Orion Star A211 model device used for pH measurement is shown in Figure 3.13.

Figure 3.13: pH meter and in situ measurement.

3.4.2 Temperature, color, and odor

The current room temperatures in the laboratory where the reactor is located were recorded by sensors showing the laboratory ambient temperature. The temperatures of the raw WW in the feed tank and the treated GW from the VFCW system were measured with the WTW 2FD46E Multi 3420 Multiparameter Meter shown in Figure 3.14.

Figure 3.14: Temperature meausements.

3.4.3 Dissolved oxygen

Dissolved oxygen (DO) levels of raw and GW treated in lab-scale VFCW were measured instantaneously in-situ. In addition, in order to test the consistency, DO levels were also measured in DSI Laboratories within the same day, taking into account the appropriate sampling and storage conditions. The temperatures of the raw WW in the feed tank and the treated GW from the VFCW system were measured with the WTW 2FD46E Multi 3420 Multiparameter Meter. The device used for temperature measurements is shown in Figure 3.15.

Figure 3.15: The WTW Multi 3420 model device used for DO measurements.

The odor and color status of crude GW and treated GW were constantly visually inspected.

3.4.4 Total suspended solids (TSS)

TSS values were analyzed in accordance with the APHA standard method. Millipore filters and 100 mL sample were used for the determination of suspended solids. After the TSS determination, the sample was kept in the muffle furnace and the volatile suspended solid (VSS) determination was also carried out.

3.4.5 Chemical oxygen demand (COD)

COD measurements analyzed in ITU Environmental Laboratories were carried out in accordance with the APHA method. Kits were used in the COD experiments carried out in DSI’s accredited Chemistry Laboratories. The results obtained were compared with the study in the literature using hotel GWs and their relative consistency was observed. Some of the collected samples analyzed are shown in the Figure 3.16.

Figure 3.16: Some of the collected samples analyzed.

3.4.6 Total nitrogen (TN), ammonia-N, nitrite-N and nitrate-N

In this study, total nitrogen (TN), ammonia-N (NH_4-N), nitrite-N (NO_2-N) and nitrate-N (NO_3-N) measurements were performed. TN, NH_4-N, NO_2-N and NO_3-N measurement was measured in accordance with the APHA standard DSI’s accredited Chemistry Laboratories, and also TN measurement in ITU Environmental Laboratories was measured with kits with a range of 5-40 mg/L from Hach-Lange. Images of the kits and the application procedure are shown in Figure **3.17** below.

Figure 3.17: Total nitrogen measurement kit and application procedure.

The measurement ranges determined for the kits show that if the results are between these values, it gives correct results. After the necessary procedures for the kits were applied, measurements were made with the Hach-Lange branded spectrophotometer in the ITU MEMTEK Laboratory. The image of the measuring device is also shown in Figure 3.18.

Figure 3.18: Spectrophotometer and sample measurement result for TN.

3.4.7 Total phosphorus (TP)

TP determination was also performed with Hach-Lange brand kits, similar to TN determination. Kit readings for TP were chosen to be 0.5-5 mg/L. After performing the procedures, measurements were performed using the spectrophotometer used for TN. The image of the measuring device is also shown in Figure 3.19.

Figure 3.19: Spectrophotometer and sample measurement result for TP.

4. RESULTS AND DISCUSSION

4.1 Results

4.1.1 Greywater characterization

The GWs were periodically taken from a big hotel in Istanbul into clean water bins and transferred to ITU Environment laboratories for GW characterization. GW samples, which were kept at 4°C in the cold room until the experiment, were characterized both in ITU Environmental Biotechnology Laboratory and in the Chemistry Laboratory of the 14th Regional Directorate of State Hydraulic Works. For the characterization of hotel GWs, COD, TSS, TN, TP, NH_4-N, NO_3-N and pH, temperature and DO measurements were made. The results obtained as a result of characterization studies of raw GW used in lab-scale VFCW are listed in Table 4.1.

Table 4.1: Raw GW characterization.

Parameter	Average	Min. – Max.
pH	7.32	7.22-7.40
T, *(°C)*	27.1	26.4 – 27.9
DO, *(mg/L)*	2.05	1.78-2.32
TSS, *(mg/L)*	41	28-54
COD, *(mg/L)*	104.4	47.6-185
TN, *(mg/L)*	13.1	8.6-15.7
NH_4-N, *(mg/L)*	2.1	1.62-2.51
NO_3-N, *(mg/L)*	0.24	<0.05-0.34
NO_2-N, *(mg/L)*	<0.109	<0.109
TP, *(mg/L)*	1.81	0.99-2.67

As noted in the previous sections, GW characterization is dependent on many factors and is variable. Just as it varies from country to country, it also varies from residence to residence. It may even vary according to the seasons and certain times. GW, which was used in the lab-scale VFCW system throughout this study and was collected from the GW line of the hotel 4 times in total and then characterized, was compared with the TÜBİTAK study to determine the consistency of the characterization experiments.

The data to be used as a comparison are in the feasibility report submitted by TUBITAK and within the scope of this study, wastewater parameters of hotel raw GW were monitored for about a year. These data were compared with the GW characterization data used in VFCW and presented in the Table 4.2.

Table 4.2: Comparison of characterization results with TÜBİTAK study.

Parameter	In this study		In the TÜBİTAK study	
	Average	Min. – Max.	Average	Min. – Max.
pH	7.32	7.22-7.40	7.45	7.12-7.71
T, *(°C)*	27.1	26.4 – 27.9	-	-
DO, *(mg/L)*	2.05	1.78-2.32	-	-
TSS, *(mg/L)*	41	28-54	66	10-468
COD, *(mg/L)*	104.4	47.6-185	105	<30-470
TN, *(mg/L)*	13.1	8.6-15.7	7.4	<0.5-43
NH_4-N, *(mg/L)*	2.1	1.62-2.51	1.44	<0.05-6.8
NO_3-N, *(mg/L)*	0.24	<0.05-0.34	-	-
NO_2-N, *(mg/L)*	<0.109	<0.109	-	-
TP, *(mg/L)*	1.81	0.99-2.67	3.2	0.4-8.8

When the results obtained are compared with the results of the TÜBİTAK study and other studies in the literature, very extreme values were not found in terms of maximum, minimum and average values. Since the TÜBİTAK study was carried out at the time of the pandemic, it is a necessity to consider and examine the changes caused by the pandemic in the evaluation of the characterization studies. While collecting WW from the hotel GW line for the VFCW system, conditions such as the day of the week, time of day and even the population status in the hotel were taken into account. Comparisons have been made in this regard. It has been observed that the COD values obtained within the scope of the thesis are very close to the values in the TUBITAK study. When the COD values were compared with other literature studies, it was observed that the measured COD was much lower. The main reason for this is that kitchen WW is not included in the hotel GW collection system. The fact that kitchen WW with a high organic content was not fed into the GW line showed that the measured COD values were lower than the literature data. Therefore, it can be said that the GW used in the VFCW system is light GW in terms of COD.

pH values are close to the literature data. It did not show much variation among collected GW samples. In terms of pH, since the laundry WW is not included in the GW line, the collected GW has a light GW feature. The pH range of laundry GWs is greater due to the use of high amounts of detergent. Although there is not much data in the literature for DO levels, it is low as expected.

As for N and P, they do not have very high values in the GW collected, since kitchen and laundry GW is not included in the GW line. The main source of N and P content available are cleaning products from bathrooms and sinks. The fact that the P content is low compared to the TÜBİTAK study can be attributed to the shortage of guests in the hotel during the GW sampling periods. These results are an indication that hotel GW are a light GW.

4.1.2 Treatment performances of wetland reactor

After the characterization studies of the raw GW were made, the GW was taken into operation in the VFCW. The operating conditions were selected based on the studies in the literature and operated as a batch reactor. This operating method, which is parallel with tidal flow in the literature, operates according to an intermittent feeding method.

In this thesis, it was studied in parallel with the "tidal flow method", which mostly works as feed-contact-discharge-rest in the literature. In the method applied in this study, the VFCW system was fed by dripping gray water and the feeding process was stopped after the system reached saturation. Unlike the studies in the literature, the system was not kept in the contact phase additionally because the feeding process was performed dripping and the feeding phase took longer than the studies in the literature. In the feed mode stage, the gray water entering the system through homogeneous distribution channels was contacted with the components of the VFCW system. In this feed-contact phase, pollutants in the GW were removed by various treatment processes. At this stage, the plants uptake the nutrients in the GW. At the same time, contaminants are attached to the filter media by adsorption. On the other hand, a biofilm layer is formed in the system environment and a suitable environment for microbial communities is prepared. After the VFCW bed reached saturation, the discharge phase was started. The discharge of GW in the VFCW bed was also slow, as was the feed phase. Thus, the contact time of the GW with the VFCW components has been increased as much as possible. During the discharge phase, the pores in the VFCW substrate are filled with air, which allows the system to return to aerobic conditions. After the GW in the system is completely discharged, the resting phase is started. And the system is kept on hold until the next feeding. Thus, a cycle is completed. This is also described as a pulse in the literature. The removal performances of the lab-scale VFCW system on pollutants in the GW are summarized in the table.

Table 4.3: The removal performances of the lab-scale VFCW system.

Parameter	Influent	Effluent	Removal Rates (%)
pH	7.32	7.2-7.5	-
T, *(°C)*	27.1	26.4 – 27.9	-
DO, *(mg/L)*	2.05	7.93	-
TSS, *(mg/L)*	41	5.7	86
COD, *(mg/L)*	104.4	15.6	85
TN, *(mg/L)*	13.1	7.1	45
NH_4-N, *(mg/L)*	2.1	<0.132	93
NO_3-N, *(mg/L)*	0.24	4.32	-
NO_2-N, *(mg/L)*	<0.109	<0.109	-
TP, *(mg/L)*	1.81	0.34	81

The removal performances of the lab-scale VFCW system on pollutants in the GW are presented below one by one.

4.1.2.1 pH

The pH of the raw GW was 7.32 on average. In treated GW, this value was between 7.2-7.5 on average.

4.1.2.2 Temperature, color and odor

The lowest temperature was measured as 21.5 and the highest temperature as 26.5. Treatment of GWs in VFCWs using plants showed a reasonable reduction in color and odor. While the color of the incoming water was gray, there was a significant decrease in the test time gradually from gray to transparent. A slight unpleasant odor occurred at the initial stage of the treatment process. It has been stated in the literature that this is due to the sulfur in the GW. No such bad odor was observed after the treatment process. It can be concluded that a small amount of sulfur is also removed before processing.

4.1.2.3 COD

The average COD removal efficiency of the VF reactor was 85% removal within the first cycle. The COD load removal efficiency was 15.6 g/m^2·d. Compared to other studies in the literature, these rates are at a high level. The COD kinetics for the lab-scale VFCW reactor are shown in Figure 4.1, Figure 4.2, Figure 4.3 and Figure 4.4.

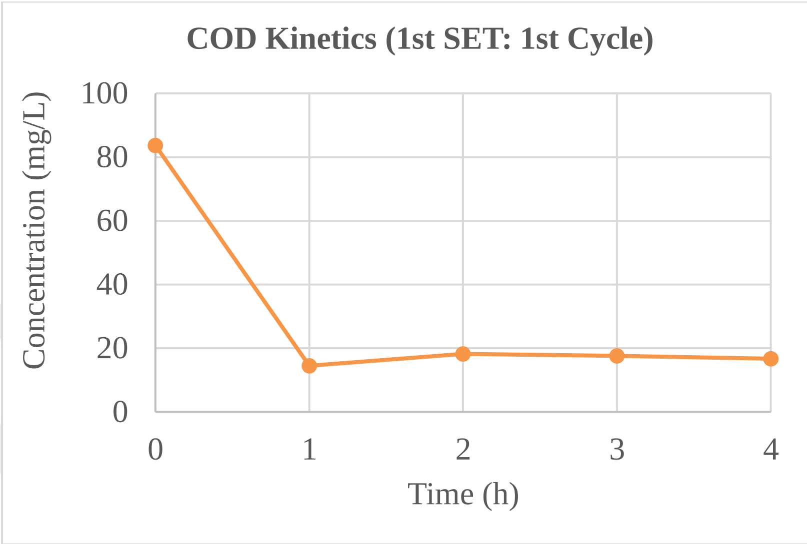


Figure 4.1: COD kinetics (1st SET: 1st cycle) for the VFCW.

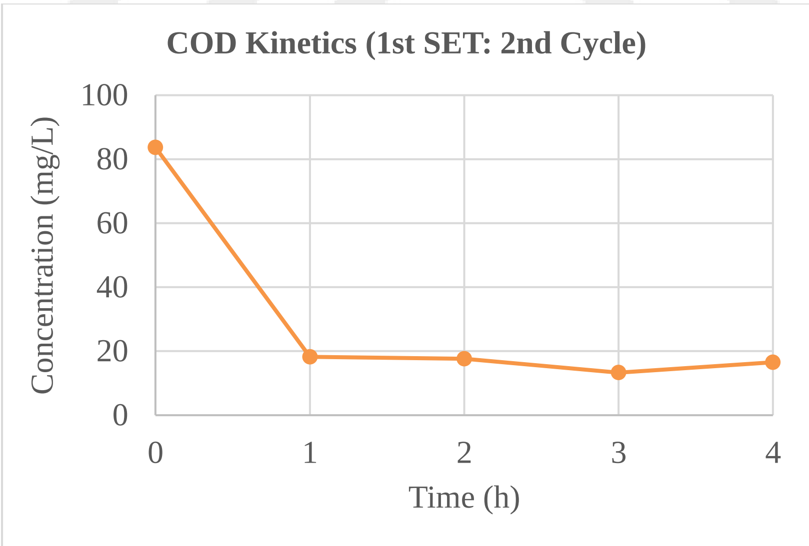


Figure 4.2: COD kinetics (1st SET: 2nd cycle) for the VFCW.

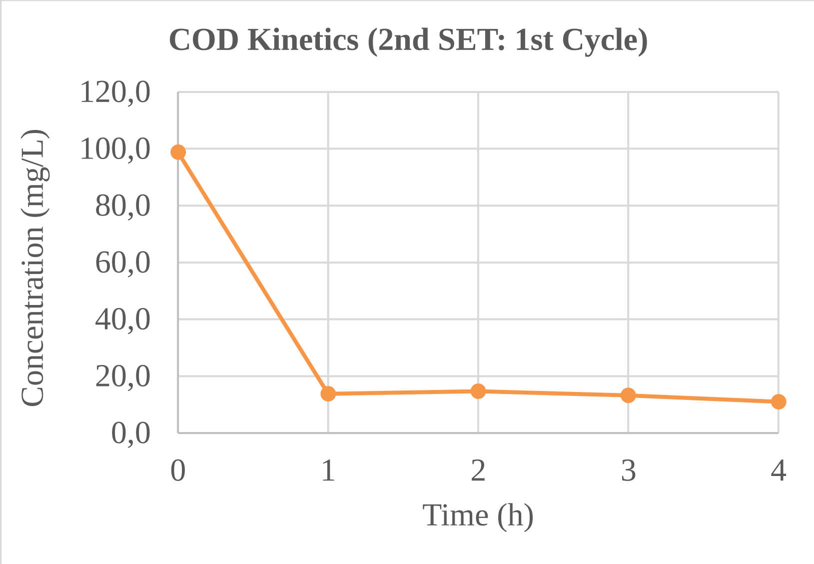


Figure 4.3: COD kinetics (2nd SET: 1st cycle) for the VFCW.

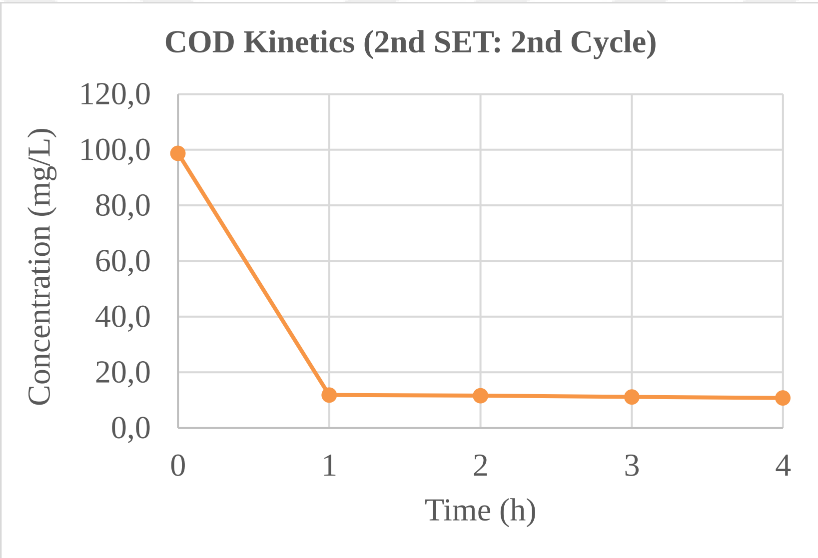


Figure 4.4: COD kinetics (2nd SET: 2nd cycle) for the VFCW.

4.1.2.4 TN, NH_4-N, NO_2-N, NO_3-N

The average TN removal for the VFCW reactor efficiency was 45%. Load removal efficiency was 1.1 g/m^2·d. At the beginning, NH_4-N concentrations decreased accompanied by an increase in NO_3-N concentrations. After the 1st hour, NO_3-N concentrations decreased and TN removal was observed. The TN and NO_3-N kinetics for the lab-scale VFCW reactor are shown in Figure 4.5, Figure 4.6, Figure 4.7 and Figure 4.8.

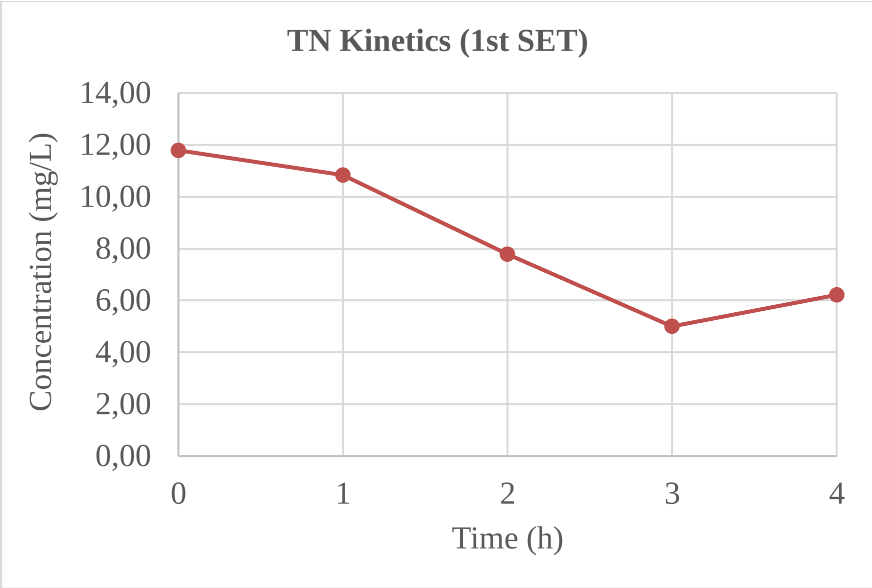


Figure 4.5: TN kinetics (1st SET) for the VFCW.

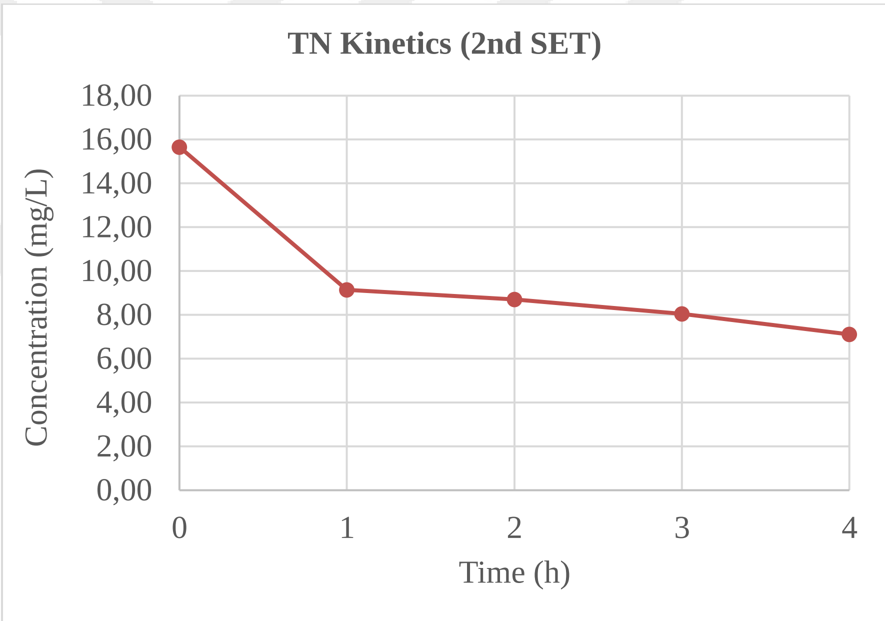


Figure 4.6: TN kinetics (2nd SET) for the VFCW.

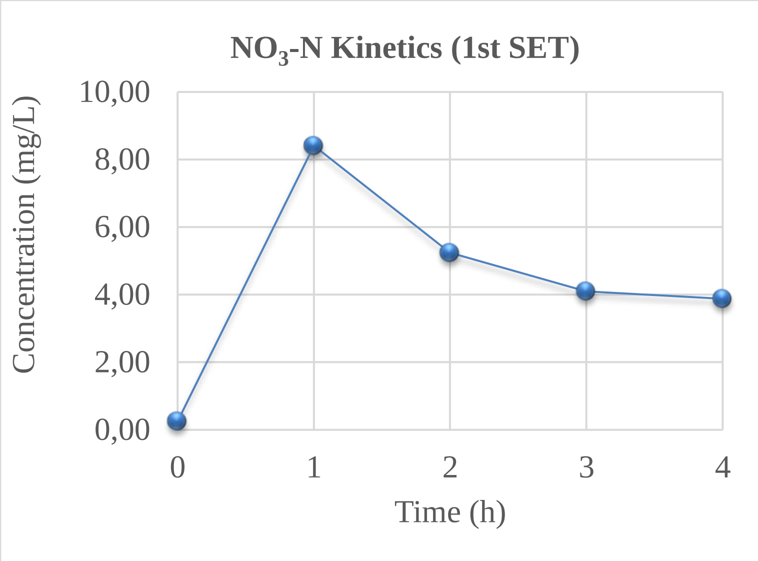


Figure 4.7: NO_3-N kinetics (1st SET) for the VFCW.

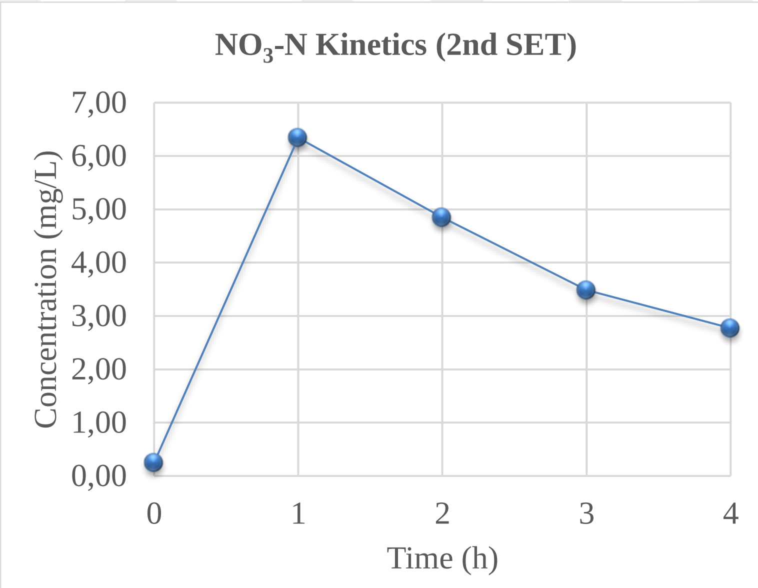


Figure 4.8: NO_3-N kinetics (2nd SET) for the VFCW.

4.1.2.5 TP

TP concentrations also rapidly decreased mostly due to the adsorption to the filter media. The average TP removal for the VFCW reactor efficiency was 81%. Load removal efficiency was 0.4 $g/m^2 \cdot d$.

4.2 Discussion

4.2.1 Examining the outputs in terms of greywater reuse

When the reuse standards of the purified GW and the pollutant concentrations of the purified GW in the VFCW reactor are examined, it can be concluded that the reuse standards are met if the microbiological indicators are determined and disinfected. Although using as reservoir water and using in landscape irrigation are prominent reuse alternatives, it can be said that treated GW can be used in any area where there is no human contact and where mains water is used.

Although there is no specific standard for the reuse of GW for Türkiye, there are standards for the reuse of wastewater. In this context, two areas of reuse stand out, namely the irrigation of vegetables and fruits consumed without cooking and by cooking. As can be understood from the explanation, lower concentrations are specified for foods that are consumed without cooking. The parameters to be considered are BOD, TSS, pH, turbidity and fecal coliform amount. It is necessary to expand the studies on this subject, increase the parameters, and thus expand and privatize the usage areas. When the results obtained are compared with the standards, it can be said that the desired output concentrations are obtained in BOD, TSS, pH and turbidity parameters. Although the BOD measurement was not done separately, since it is known that the BOD value can never be greater than the COD value, the 14 mg/L value obtained in the study is less than the minimum value given as the standard, 20 mg/L, indicative of the standard being met. No measurement has been made for fecal coliform, but it is known that microbiological indicators are not significantly removed in artificial wetlands as a result of literature research. For this reason, it will be possible to meet this standard by using the CW and disinfection unit together.

5. CONCLUSIONS AND RECOMMENDATIONS

In this study, the evaluation of treatment performance and reuse areas of GWs in CWs, which is a natural treatment technology, were investigated. The problem of water scarcity is an important problem. Population growth increases the demand for clean water resources. Therefore, it has become a necessity to reduce the use of limited natural resources and to reuse the used resources by recycling. The use of natural methods for reuse is important for sustainability. Although traditional technologies with high energy consumption and investment costs have high treatment efficiencies, more sustainable technological solutions need to be produced. In this thesis study, it can be said that natural purification methods have not negligible effects when compared to traditional purification methods. The fact that energy and consumable consumption is almost non-existent, and besides, it provides efficient treatment facilities bring these technologies to the fore. The use of these systems, which also carry multi-faceted ecological benefits, especially in WW treatment with low pollution load such as GW, facilitates sustainable management activities. Therefore, in this study, the treatment performances of GW in CWs and the reuse possibilities of treated GW were investigated. This study contributes to GW treatment methods and optimization. It also provides a better understanding of the design and operational considerations for artificial wetland technology for GW reuse. In this section, this scope has been detailed and suggestions have been presented for the study, and it has been tried to shed light on future studies.

5.1 Greywater Reuse and Sustainability

Sustainability is ensuring the stable continuity of a process without interruption. The reuse of gray water is also part of the sustainability goals. Because GWs are not very polluted waters. Therefore, their treatability is easy and manageable. Especially due to urbanization and industrialization, the pressure on WWTPs in big cities has increased. High investment and operating costs are another problem. However, if there is no good facility design and operation, the possibility of chain problems in terms of environmental pollution management increases. In this regard, it is essential to use more sustainable and green technologies. One of these technologies, CWs, are systems with proven efficiency in WW treatment. More compact and innovative designs of these systems, which are designed as decentralized treatment systems, will increase the applicability of these systems. Collecting GWs separately and treating it in CWs has certain difficulties, but it is not very difficult. Especially light GWs can be easily treated without the need for advanced technological treatment. Therefore, it is possible that gray water can be reused in many areas. These waters can be reused in homes, workplaces, social environments, in short, in all areas of life.

The resource recovery strategy reduces the environmental impacts of conventional wastewater treatment. It reduces the cost of treatment by producing some of the required energy and enabling the recovery of valuable products. This strategy contributes to the ultimate goals of the wastewater treatment process. These can be listed as maximizing COD removal, minimizing energy consumption and reducing sludge production. In general, resource recovery helps offset the cost associated with industrial wastewater treatment. It provides the foundation for the circular economy to produce more food, energy and water while reducing environmental pollution.

The three basic parameters common to all regulations and guidelines for controlling the quality of recovered water are OM (BOD_5, COD), TSS and microbial population. TSS below 20 mg/L provides a clear effluent. A BOD_5 concentration of less than 20 mg/L has been recommended to limit microbial activities. As a result, pollutants below the detection limits according to all standards were considered acceptable.

It is worth noting that meeting the specified standards does not mean that the reuse of recovered water is safe. The parameters selected90 in one embodiment are generally limited to three to six features. Therefore, these parameters may not be representative of all pollutants in gray water. The presence of certain pollutants, such as xenobiotic organic compounds, can have far more dangerous effects. Consequently, the number of parameters effective in these arrangements should be increased.

5.2 Recommendationsions

Under this heading, there are proposed future studies and solutions for GW treatment, as well as end-use alternatives. In addition, useful outputs of using CWs for GW treatment in integration with other systems will be mentioned.

5.2.1 System choice and design concept

As can be seen from the results, especially nitrification-denitrification processes can be performed more efficiently in VFCWs, which will bring these systems to the forefront. In such N removal, its effectiveness will gradually increase and it will give much more satisfactory results. In this regard, the creation of hybrid systems can increase these removal efficiencies. However, the disadvantage of hybrid CWs is that they require much more land area. Already, this is a problem for all CWs, especially in urban areas. In order to overcome this problem, system designs must be made in a way that takes into account both environmental compatibility and conditions that will provide high removal rates. On the other hand, reaching the optimum depth of wetland beds will further reduce the land area requirements of these systems. It will be beneficial to focus on these issues in future studies. However, system designs should be made not only for non-potable uses, but also for potable uses. However, creating designs in these systems in such a way that it is possible to produce energy while treating wastewater on the one hand will be an alternative solution for every country in a period of energy crisis.

5.2.2 Sustainable WW treatment in Türkiye

Türkiye is an energy dependent country. Although new projects have been carried out in recent years to reduce foreign dependency in energy, natural disasters such as political and economic volatility can bring unexpected results. Especially as a result of the mucilage incident in the Sea of Marmara, the issue of WW management became the main agenda item. Although various strategic plans such as directives, regulations and sanctions have been put forward, there are still deficiencies in the implementation of these strategies.

Nature-based solutions (NBSs) such as VFCW or other types of CWs are very realistic and viable solutions for WW treatment and management. Although natural treatment methods such as CW come to the fore from time to time, it is still very difficult to show an example of a good CW plant in Türkiye. It is possible to find suitable lands for CWs in all urban-rural regions, including densely populated areas. However, the scarcity of qualified personnel specialized in CW causes the public to benefit from these systems for a very short time. In short, although wetlands are built in certain places in Turkey, they are left to their fate due to neglect and improper management. The fact that water scarcity is also felt in our country necessitates the sustainable management of wastewater. Moreover, Turkey, which is one of the countries that need to manage its economic resources very well, investing its own economic resources for traditional technologies and not getting the expected response from these systems makes wastewater management much more essential. Alternatives to these traditional systems have to be tried because of the very high initial investment costs and the very serious energy consumption.

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