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Using of Constructed Wetlands in The Treatment of Wastewater: A Review for Operation and Performance

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ABSTRACT

Wastewater recycling for non-potable uses has gained significant attention to mitigate the high pressure on freshwater resources. This requires using a sustainable technique to treat natural municipal wastewater as an alternative to conventional methods, especially in arid and semi-arid rural areas. One of the promising techniques applied to satisfy the objective of wastewater reuse is the constructed wetlands (CWs) which have been used extensively in most countries worldwide through the last decades. The present study introduces a significant review of the definition, classification, and components of CWs, identifying the mechanisms controlling the removal process within such units. Vertical, horizontal, and hybrid CWs were used to treat different types of wastewater from individual households, waste disposal sites, oil refineries, agricultural production, and tannery effluent. The effects of several design and operational factors related to the type of plant, substrate, and flow direction are studied and surveyed in this work to be the starting point for researchers in future investigations.

Keywords: Heavy metal, Sand material, Treatment, Flow, Hybrid.

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استخدام الأراضي الرطبة المشيدة في معالجة مياه الصرف الصحي: مراجعة للتشغيل والأداء

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الخلاصة

لقد حظيت إعادة تدوير مياه الصرف للاستخدامات غير الصالحة للشرب باهتمام كبير للتخفيف من الضغط المرتفع على موارد المياه العذبة. وهذا يتطلب التركيز على استخدام التقنية المستدامة لمعالجة مياه الصرف الصحي البلدية الحقيقية كبديل للطريقة التقليدية خاصة في المناطق القاحلة وشبه القاحلة. إحدى التقنيات الواعدة المطبقة لتحقيق هدف إعادة استخدام المياه العادمة هي الأراضي الرطبة المشيدة (CWs) التي استخدمت على نطاق واسع في معظم دول العالم خلال العقود الماضية. تقدم الدراسة الحالية مراجعة مهمة حول تعريف وتصنيف ومكونات الأراضي الرطبة المشيدة مع تحديد الآليات التي تتحكم في عملية الإزالة التي حدثت داخل هذه الوحدات. تم استخدام الأراضي الرطبة المشيدة العمودية والأفقية والهجينة في معالجة أنواع مختلفة من مياه الصرف الصحي الناتجة عن المنازل الفردية ، ومواقع التخلص من النفايات ، ومصافي النفط ، والإنتاج الزراعي ، ودباغة النفايات السائلة وغيرها. تمت دراسة آثار العديد من عوامل التصميم والتشغيل المتعلقة بنوع النبات والركيزة واتجاه التدفق ومسحها في هذا العمل ليكون نقطة البداية للباحثين في الأبحاث المستقبلية.

الكلمات الرئيسية:عنصر ثقيل، مادة الرمل، معالجة، تدفق، هجين.

1. INTRODUCTION

Water pollution has been the primary threat to the global environment in recent decades. As a result of human efforts to improve all aspects of life, there is a noticeable decline in the quality of surface- and ground-water. For instance, improper sewage disposal (or wastewater) from residential, commercial, and industrial sectors can significantly pollute receiving water bodies. Also, development in the industry field leads to producing large quantities of wastewater. In addition to contributing to the already worsening energy problems, the generated wastewater and its environmental pollutants have become an obstacle to these developments **(Abdulmajeed and Ibrahim, 2018)**. As a result, "water pollution" refers to any alteration in the water's physical, chemical, or biological properties that adversative effects. The effects of this pollution are harmful not only to human life but to the entire ecosystem **(Faisal and Badah, 2021).**

Wetlands are referred to as "Earth's kidneys, living mechanisms of the environment" because they absorb compounds like phosphorus and nitrogen that may be in excess in the waterways, making them the most effective means of cleaning polluted water. Due to the significance of these means, many communities are taking severe steps to protect, restore, and even create wetlands. Natural wetlands are one-of-a-kind environments home to various biological processes and exhibit characteristics of aquatic and terrestrial domains. They are an area of transition between water and land. Definition of "natural wetlands" **(Stefanakis et al., 2014)**: "areas of marsh, fen, peatland or water, permanent or temporary, with water that is static or flowing, fresh, brackish or salt, including areas of marine water the depth of which at low tide does not exceed six meters."

Constructed wetlands (CWs) consider common engineered systems utilized in wastewater treatment resulting from rural and urban regions; such systems' design is characterized by reliability, simplicity, low cost, and environmental compatibility **(Kumari and Tripathi, 2014)**. The CW, supported by a wide range of available plants, can be an alternative technology for eliminating toxic waste, organics, pathogens, nutrients (nitrogen and phosphorous), and suspended solids from wastewater **(Gikas et al., 2013)**. Therefore, it is valuable to study the controlling mechanisms responsible for contaminant reduction using various designs and configurations, single-stage design **(Kumari and Tripathi, 2014)** or multiple stages for wastewater treatment to ensure higher efficiency **(Bilgin et al., 2014)**.
Nitrogen, phosphorus, heavy metals, suspended solids, and organics are widespread contaminants in the aquatic environment, which can be removed by CWs depending on the substrate, plant, and activity of microorganisms **(Fountoulakis et al., 2009)**.
Surface water bodies such as oceans, ponds, and rivers can receive uncontrolled discharges of nutrient-rich wastewater. Therefore, it is essential to separate organics and nitrogen compounds from influents in such engineered ecosystems **(Chen et al., 2011)**.
For wastewater obtained from the residential sector, several techniques like oxidation ponds and activated carbon are applied; however, the construction, operation, and maintenance of such techniques require high costs **(Imron et al., 2019)**. Hence, CWs can be an efficient alternative to traditional methods of treating wastewater rich with organics and nitrogen.
Usage of CWs in organics and nutrients removal can represent a good solution for exceeding; a) the “eutrophication of lakes and rivers” resulting from a discharge of nitrogen into a water body **(Liang et al. 2011)**, b) the “generation of dead zones” within open water channels due to the depletion of dissolved oxygen in the elimination of untreated organic material. In comparison with surface flow wetlands, subsurface flow units have high efficacy in removing organics, according to recent studies; however, the treatment efficiencies of nitrogen in such systems are relatively poor **(Saeed and Sun, 2012)**.
The reuse of raw wastewater for irrigating crops in many suburban regions of the cities may be caused severe health risks for farmers and consumers of crops that may be contaminated. In addition, the spreading of the population in the villages and the high cost of sewage collection can represent reasonable justifications for the construction of decentralized plants (i.e., CWs) for wastewater treatment. These plants are considered a feasible alternative to traditional sewage treatment methods, which can interest the population **(Li, 2010)**. The CW is a low-cost method that supports the wildlife habitat and aesthetic value and creates usable plant biomass. This technique was used effectively worldwide for remediating; municipal sewage **(Song et al., 2009)**, tannery effluent **(Saeed and Sun, 2012)**, refinery wastewater **(Robert et al., 2008)**, and eliminating emerging organic pollutants **(ávila et al., 2013)**.
The present work introduces an intensive review of basic concepts, classification, components, functionality, and removal mechanisms of CWs units. This can be represented as a concrete base for researchers to apply new ideas especially related to using alternative options for substrate, vegetation, and deep investigation for mechanisms controlling the elimination of familiar pollutants from a wastewater stream.

2. DEFINITION OF CONSTRUCTED WETLAND

CWs are artificial systems for treating wastewater and consist of shallow (< 1 m deep) channels or ponds supported by aquatic plants. The treatment of influent wastewater occurs through physical, chemical, and biological operations. The CW is an engineered structure (supplied with synthetic liner) packed with rock, gravel, or sand to govern the direction of flow, liquid detention period, and water elevation. Research on the utilization of CWs began in the 1950s at the Max Planck Institute in Germany by Käthe Seidel, who noticed that plants grew in polluted water (wastewater) better than in relatively unpolluted water. The possibility of lessening the over-fertilization, pollution, and silting up of inland waters through appropriate plants was observed during the experiments. There is an opportunity for allowing the contaminated waters to support life again". It was noticed that macrophytes like Phragmites australis could remove large quantities of inorganic and organic materials from wastewater.

Furthermore, bacteria in the polluted water could also be eliminated by macrophytes. These findings began modern CWs and stimulated the research to implement such wetlands in the Western world **(Zhang, 2012).** Efforts in the USA were directed to install some CWs during the 1970s, and these wetlands increased in the 1980s. The CWs were utilized to treat various types of wastewater from individual households, waste disposal sites, oil refineries, agricultural production, and others **(Stanković, 2017)**.

3. CLASSIFICATION OF CONSTRUCTED WETLANDS

The CWs can be implemented with various configurations **(Haberl, 1999)** based on the; 1) life form of macrophytes (submerged, emergent, free-floating), 2) pattern of flow (free water surface flow, subsurface flow), 3) type of wetland cells (hybrid, one-stage, multi-stage), 4) kind of influent, 5) degree of treatment for wastewater, 6) effluent and influent structures, 7) type of substrate and 8) type of wastewater loading. The main classifications of CWs can be listed in the following subsections.

3.1. Free Water Surface Constructed Wetlands (FWS CWs)

They are identical to the natural marshes, which can be planted with floating, submerged, and/or emergent macrophyte plants. The influent wastewater is moved overland with a free surface and at low velocities above the substrate, where the filtration, sedimentation, adsorption, and precipitation will be the mechanisms governing the treatment process. Many studies signified that these systems are effective in removing pathogens because of the high exposure to the ultraviolet ray within sunlight due to the low flow rate of wastewater. Therefore, these systems can be adopted as a tertiary (polishing) stage. The FWS systems are susceptible to temperate climates, and their efficiencies can be reduced during low temperatures because of the decrease in detention time and effective water depth **(Kadlec, 2009; Kotti et al., 2010; Stefanakis, 2018; Vymazal, 2013)**.

3.2. Subsurface Flow

This technology was applied at the previous century's end to treat the wastewater generated from single houses, institutions, and small settlements. The SSF CWs are basins filled with some filter materials (substrate), where the contaminated water is injected to remain below the substrate surface and moves around the roots of plants. After a specific duration, the treated water was discharged from the basins through a structure that maintained the wetland's specified water depth **(Andreo-Martínez et al., 2016)**. Previous literature elucidated that the SSF system has different names, such as planted soil filters, vegetated submerged beds, reed bed treatment systems, gravel bed hydroponic filters, and vegetated gravel beds. The SSF CWs can classify according to the water distribution method into several types, as listed below **(Vymazal, 2005; Vymazal, 2007; Saeed and Sun, 2012)**.

1) Vertical flow constructed wetlands (VFCWs): Macrophytes are common plants used in VSSF CWs where the bed consists of multi-layers of sand and gravel to form a depth from 0.45 to 1.20 m. At the same time, the slope of the bottom varies from 1 to 2% to facilitate the collection of effluents. The wastewater is injected on the substrate surface and moves in the vertical path until collected at the bed bottom by an underdrain system. The approach adopted in the wastewater distribution on the surface of the substrate can create an aerobic environment by driving fresh air to the pores within the solid matrix **(Stefanakis et al., 2014)**. So, this considers a unique property for VF CW compared with the HF system because fresh air can enhance the degradation and nitrification processAbou-Ella. Accordingly, previous studies certified that this system can eliminate COD, BOD, and SS from wastewater pollutants **(Brix and Arias, 2005)**. On the other hand, this system can't support the denitrification process, and consequently, nutrient removal is limited **(Rustige et al., 2003)**. VFCWs are implemented on the field scale in countries like the USA, UK, Austria, Denmark, Germany, France, Brazil, and others in Asia and Africa **(Stefanakis et al., 2014)**.

2) Horizontal flow constructed wetlands (HFCWs): The polluted water enters such a system through a specific inlet and can flow slowly within the substrate's voids and around the plant's roots. This water continues propagating in the horizontal path below the bed surface until collected from the outlet. The water surface is not imposed to the atmospheric pressure as in FWSF CWs but will be below the bed surface at about 5-15 cm. This assists in inhibiting mosquito breeding, and accordingly, the health risks for wildlife habitats and humans can be reduced. Usually, the bed consists of gravel or sand mixed with gravel to support plant growth, and the depth of this bed may range from 30 to 80 cm. The extension of the plant roots is the most critical parameter used to specify the depth of the bed. To ensure the flow of the wastewater occurs under gravitational effects, the bottom of the HF CW unit must be inclined with a slope varied from 1 to 3%. Within this system, anaerobic and aerobic zones can be generated to facilitate wastewater degradation. Previous literature on this system proved that biofilms could grow with the assistance of the substrate and plant roots; this will enhance the elimination of suspended solids and organic matter while removing phosphorus and nitrogen remains small **(Rousseau et al., 2004)**.

3) Hybrid-constructed wetlands: They are taken from the original hybrid system presented by Seidel at the Max Planck Institute in Krefeld, Germany. The system layout includes 2 stages; several VF beds in parallel alignment and 2 or 3 HF beds in a series scheme. These beds can be vegetated with Phragmites australis, Iris, Carex, Typha, or others. To improve the efficacy of treatment specifically for nutrients, several kinds of CWs can be combined. The vertical system provides the suitable conditions required for nitrification due to the high capacity of oxygen transport; however, limited or no denitrification enhances the usage of a hybrid system (or combined system). Frequently, this system consists of VF and HF units arranged in a staged scheme, and the advantages of these units can be complemented **(Cooper, 1999)**.

4. CHOICE OF SUBSURFACE FLOW OVER SURFACE FLOW

The FWS CWs dominated North America, while the SSF CWs were chosen in Europe and Australia **(Vymazal, 2011)**. When comparing these two types of constructed wetlands, previous studies proved that the first one is generally cheaper in construction and simpler in design than the second one. The FWS CWs are easy to construct, operate, and maintain with greater flow control than SSF CWs. Due to the possibility of human exposure to pathogens, SF units are seldom utilized for secondary remediation; these units could be more appropriate for advanced treatment. Although the SSF CWs are more expensive than SF wetlands, they demonstrate a good ability to tolerate flow fluctuations besides the operation and maintenance simplicity **(Robert and Wallace, 2008)**. They are applied for secondary sewage remediation from small communities or single homes.

5. CHOICE OF VERTICAL FLOW OVER HORIZONTAL FLOW

When considering the decreased area demand of subsurface flow over surface flow, higher oxygen transfer rate of VSSF CW, and nutrients, vertical flow CWs are better for sewage remediation in urban and rural regions as well as for wastewater generated from the agricultural sector Because the VSSF improves the process of nitrification and degradation. The flow of influent into VSSF CWs is generally worked under pressure and distributes the sewage uniformly along the substrate surface; pumps are often installed and used for this purpose **(Rehman et al., 2017)**. Usually, the HF units can operate without external energy (without pumps). The nitrification in this wetland is poor because of the lower oxygen intrusion to the filter bed compared with VF units used for higher ammonia applications. The HF wetlands can remediate the combined sewage similar to the VF units if they have suitable hydraulic dimensions. This means the HSSF effectively reduces SS and organic matter and removes bacteria with satisfactory results.

Due to its high treatment capacity compared to SF and HSSF, the VSSF system can use efficiently in the remediation of highly concentrated wastewater. Raw sewage was applied to VF CW units in a French version of the technology **(Meyer et al., 2013),** and also activated sludge may be dewatered in the VF system **(Uggetti et al., 2010)**. The advantage of the VF's unsaturated medium property, which offered sufficient oxygen leading to more COD degradation than HSSF during treatment, was proved **(Felde and Kunst 1997).**

6. CWs FOR WASTEWATER TREATMENT

Seidel was the first scientist who studied the possibility of CWs application in wastewater treatment. Then, tests on such systems were extensively implemented to eliminate pollution from wastewater in the 1960s and 1970s. Firstly, the CWs were applied for remediating conventional municipal and domestic sewage. Then, the usage of wetlands has expanded to purify wide types of wastewater like agricultural and industrial effluents, landfill leachates, mine drainage, polluted waters of lakes and rivers, and runoff generated from the highway and urban regions. The CWs have operated under different climatic conditions like humid, warm, cold, arid, and tropical **(Wu et al., 2014)**. More than 60×10^3 CWs are built in North America and Europe after the first fiebroadcale of these units in the 1960s **(Robert and Wallace, 2008)**. The CWs represent promising alternatives for treating wastewater in developing countries (for example, thousands of CWs used as treatment facilities for wastewater in China) **(Chen et al., 2011)**. Unlike FWS CWs, subsurface wetlands eliminate microbial pollution, suspended solids, organics, and heavy metals. The subsurface CWs are less cold-sensitive and easier to isolate for operation in the winter season. The nitrogen removal in such CWs depends on carbon sources and oxygen availability due to permanent water-logged conditions **(Babatunde et al., 2010).**

7. COMPONENTS OF CONSTRUCTED WETLAND

The major components utilized in the makeup of CW are tanks, plants, and substrate (sand and gravel), and invertebrates microbes can develop naturally **(Mahmood et al., 2018)**. Physical and microbial activities are the most important processes in the CWs and influence the dynamic of a filter. In this concern, the root zone hosts biological and physicochemical processes resulting from the interface of microorganisms, plants, soil, and contaminants **(Vymazal, 2011)**. The performance and reliability of the system are based on several controlled (design, operation) and uncontrolled (climate) parameters **(Meyer et al., 2013)**. A brief description of the main components of the constructed wetlands can be explained in the next sections, specifically the microorganisms, plants, and media.

7.1. Microorganisms

The biotic community of CW is generally limited to the organisms that can tolerate poor water quality, such as microorganisms available in the root zone. It can take various forms, like biofilm, bacterial colonies, etc. Microorganisms facilitate the degradation of organics and other low-molecular-weight biodegradable matters **(Mackintosh et al., 2017)**. Microorganisms live within the wetland in the water, substrate, or roots of vegetation. The biomass density can be increased depending on the degradation and consumption of the available nutrient. It causes a significant decrease in the contaminants of the wastewater. The efficiencies of wetlands are highly controlled by microbes which have a potential role in eliminating undesirable matters through their metabolism. The microorganisms exist in both anaerobic and aerobic locations within the wetland, including fungi, bacteria, algae, and protozoa; however, the water temperature is strongly influenced by microbial transformation **(Kadlec and Wallace, 2008).**

Chemical biodegradation can be a very complicated process involving a set of biochemicals, including fungi, bacteria, algae, and protozoa; however, the water temperature affects the microorganisms that remove nitrogen may include certain bacterial groups like β-proteobacteria or chemoautotrophic bacteria, and γ-proteobacteria for ammonia oxidation. Nitrification means the change of NH_4-N to NO_2-N and then converted to NO_3-N by biological oxidation. Denitrification is the production of molecular nitrogen (N_2) gaseous from nitrate-nitrogen by a microbial-facilitated process.

7.2. Wetland Plant

The macrophytes are the familiar plants used in the wetlands, and their presence may be one of the characteristics utilized for defining the wetland ecosystem. Macrophytes comprise emergent woody plants, emergent soft tissue plants, submersed aquatic plants, floating mats, and floating plants **(Robert and Wallace, 2008)**. As the treatment in CWs is achieved by microbial and physical processes, consumption of nutrients with plant aid is only quantitative significance in the low-loaded system; however, macrophytes have several intrinsic properties that make them critical constituents of CWs.

The functions of macrophytes are related to the treatment of wastewater, standards for providing wildlife habitat, and aesthetic forms for treatment systems. The macrophytes stabilize the surface of substrates, supply proper conditions for filtration, prohibit clogging in the VF system, and provide the required surface area for the growth of microbes **(Brix, 1997)**. A previous study **(Robert and Wallace, 2008)** estimated a lifetime of 1.5–2 years for Typha rhizomes, 18–24 months for Schoenoplectus rhizomes, and ≥ 3 years for Phragmites rhizomes. This means that the total growth rate for plants is greater than for aboveground parts alone. The oxygen transfer into the substrate layers by photosynthetic processes was investigated **(Wang et al., 2018)**. It supplies an oxygenated environment for microbes in the root zone and contributes available carbon needed by functional heterotrophic bacteria of roots to promote microbial growth. This essential process for the removal of chemicals, and the plants must have; 1) the ability to bear high concentrations of pollutants and salinity, 2) the maximum biomass, 3) deep roots to ensure aerobic processes in the bed, 4) the ability to living all around the year, and 5) rapid growth and spreading.

7.3. Wetland Substrate

Selection of an appropriate and uniform substrate for the filtration bed of CWs must be achieved to obtain the proper realization of mechanical, chemical, and biological purificensureprocesses due to the sufficient contact between the wastewater and the material of the substrate **(Odegaard et al., 2003)**. A coarser material has a high permeability to ensure a uniform flow through the filtration bed, but the remaining water in this zone will need a shorter duration. It is necessary to prohibit the finer grains from transporting into the bottom of the filter bed because this negatively influences permeability.
Sand and gravel are utilized frequently as substrates in the CWs. Gravel with a grading of 4-8 mm or 8-16 mm is regarded as high hydraulic permeability material ($K > 10^{-3}$ m/s), but it has a low surface area for reaction and hence a small ability for purification of wastewater **(Stefanakis and Tsihrintzis, 2012)**. It is favorable for wastewater treatment that the coefficient of hydraulic conductivity (K) for sand ranges from 10^{-3} to 10^{-4} m/s with a 0-2 and 0-4 gradation. The sand utilized in the CW beds must be washed to decrease the content of fine grains. Also, recommendations specify using sand containing a high proportion of round grain to obtain high purification potential and sufficient hydraulic permeability. To treat the mixture of rainwater and sewage, layers of gravel and sand must organize where the gravel size decreases from the bottom to the top **(Stefanakis, 2017)**.

7.4. Water

The relationship between wastewater's influent and effluent, considering the functions of vegetation, bed materials, and microorganisms, is known as wetland hydrology. The hydrology of the flow is the primary factor influencing the design of the CW because the flow's nature has established relationships between the functions mentioned above. The success or failure of CW is determined by the flow hydrology, which takes into account the contact time between water and biota; consequently, any changes in hydrology can impact CW performance. Hydraulic retention time (HRT) is important for designing and performing CW because it forms the time required to retain water in a wetland. In CW, the combination between hydrology and an aerobic condition can significantly reduce contaminants, as in the removal of nitrogen by the denitrification process.

8. REMOVAL MECHANISMS IN CONSTRUCTED WETLAND

To specify the acceptable characteristics for designing and operating CWS, it is necessary to understand the basic mechanisms responsible for the removal process. Wetlands can remove the contaminants from urban surface runoff through many mechanisms like; attachment of sediment, transformation, and degradation. The contaminants can be transferred to the groundwater or atmosphere, where the low permeable barrier (or liner) can protect the groundwater from contamination. The adsorption, sedimentation, filtration, volatilization, dissolution, precipitation, and bacterial and biochemical interactions are major chemical, physical and biological mechanisms in treating aqueous solution. Significant changes in the properties of the wetland, such as hydrology, biota, substrates, etc., can be observed. This means that the predominant treatment mechanisms can be varied from one wetland to another. These inter- and intra-wetland changes express why pollutants' removal efficiency in the wetland varies spatially and temporally.

9. HYDRAULIC LOAD AND PERFORMANCE LIMITS

While HSSF units are subjected to transient loads in field scale applications and VSSF CWs need to carry loads without minimizing oxygen exchanging, many studies are done to calculate (HL). The hydraulic load (HL) means the flow applies to the bed's surface per unit of time. It is in m/day (or cm/day) and related to hydraulic retention time by inversely proportional for a given depth of SSF CW; however, it alters from one site to another based on the wetland configuration. The target factors must be taken into account when designing of CWs as follows:

- Allowing wastewater to pass through the treatment bed with enough contact time to achieve the required treatment by the bacteria growing on the bed media before the next untreated influent dose arrives.
- They allow the transfer of sufficient oxygen and adequate growth of bacteria for processing requirements.

It is not easy to specify any compromise about hydraulic limits for CWs in the previous studies due to the difference in the usage and design of these wetlands. The characteristics of effluents suitable for different applications of water reuse and performance of treatment for combined sewerage systems (municipal wastewater and stormwater) on a hybrid system (VF-HF-FWS CW) are provided **(ávila et al., 2013)**. The VF system (with 1 bed, no dosing, and resting time) can take HL up to 0.47 m/day with satisfactory results for wastewater treatment, as reported. Depending on the wastewater nature under long-term operation, the required size for HSSF is between 3 to 5 m^2 per 150 L of water for a temperate or a warm climate and be as low as 2 m^2/capita for VSSF (The area required for VF is greater than that of HF), estimated by **(Dong, 2013)**.

10. SISIND OF WETLAND

Concerning constructed wetlands, it is necessary to urge scientists and engineers to consider one of the ecological engineering principles **(Wu et al., 2018)**; "Don't over-engineer the system; design it with nature, not against it." Accordingly, the designer must consider several parameters for dimensioning the constructed wetlands. The most appropriate design criteria include

Aspect ratio (L/W) with a value of (10/1) was used to prevent the possibility of short circulation; now, it is preferred to select a small value for this parameter, as proved by previous literature. This value was chosen as (2.3/1), and the substrate depth can be adopted as 0.6 m. This means that the volume and surface area of the bed has values equal to 2.052 m^3 and 3.42 m^2, respectively. The porosity (n) was estimated for HF and VF systems by measuring the water volume required for saturating the bed substrate. This water volume can be divided by the volume of the substrate, and the result will be the porosity of the bed. The porosity of the substrate for HF and VF systems was equal to 0.37 and 0.31, respectively. The treated flow rate is the most critical aspect of the constructed wetland design because the climatic ambient can influence it. The wet season will provide a high volume of water and, accordingly, will cause a dilution in the concentrations of contaminants compared with the concentrations in the summer months.
The hydraulic retention time (HRT) of the hydraulic pollutants within the constructed wetlands can be calculated using Eq. (1) by calculating the volume (V) of the substrate (LWD) and the flow rate (Q).

$$HRT = \frac{V}{Q_{in}} \quad (1)$$

11. KINETIC MODELING

Because several physical, chemical, and biological processes were going on simultaneously to remove contaminants from influent wastewater, the operation of CW is very complicated. Therefore, determining the impact of treatment methods on improving water quality by wetlands requires a unique mathematical representation of predominant processes. Despite the creation of sophisticated models, the majority of CW design still employs "rules of thumb" based on engineers' knowledge or simple first-order decay models **(Rousseau et al., 2004)**; however, first-order models may be not sufficient for designing of CWs **(Kadlec, 2000)**. Some models comprise first-order degradation kinetics (k). Some models forecast that the concentration of pollutants to be treated will approach zero when the retention time tends to infinity which is not consistently found in CW.
Several mathematical models are available in the previous studies for the description of the occurred processes in the CW like the first-order model, the Grau second-order model, the Sundstrom model, the Stover-Kincannon model, the Chen model, the Contois model, and the Michaelis-Menten type kinetic model **(Büyükkamaci and Filibeli, 2002; Sandhya and Swaminathan, 2006; Jafarzadeh et al., 2009)**. Grau model in Eq. (2) shows the second-order kinetic, which can be expressed as follows **(Ni et al., 2012; Faekah et al., 2020)**:

$$\frac{S_i \times HRT}{S_i - S_e} = a + b \times HRT \quad (2)$$

where S_i is the inlet chemical concentration (mg/L), and S_e is the effluent chemical concentration (mg/L). This equation can also take the following formula shown in Eq. (3):

$$S_e = S_i\left(1 - \frac{1}{b + \frac{a}{HRT}}\right) \quad (3)$$

The kinetic constants (a) and (b) are determined by fitting Eq. (3) with experimental measurements.

12. EFFICIENCY IN REMOVING POLLUTANTS

Until now, vertical, horizontal, and hybrid SSF CWs have been established to eliminate common macro-contaminants and metals from different types of wastewater (industrial, municipal, domestic) as mentioned in **(Kadlec and Wallace, 2009; Mustafa, 2013; Huang et al., 2015; Stanković, 2017)**. The performance of SSF CWs to achieve the required treatment for previous kinds of wastewater is based on the quality of the influent parameter and the required treatment to satisfy, for example, the requirements of water reuse, which might diminish the huge load on freshwater resources.

The removal of AO7 dye with 127 mg/L concentration within VF CW using aerobic degradation was monitored. The CW bed consisted of a 10 cm gravel layer at the bottom and then 77 cm sandy clay soil at the top; however, this bed was cultivated with P. australis. The measurements certified that the removal percentages of color and COD were not less than 93% for a duration reached 48 days **(Davies et al., 2006)**. The textile wastewater was treated in Slovenia by horizontal and vertical CW with a 40 m^2 area for each. The treatment's average efficiencies amounted to 5% for TN, 77% for COD, 85% for color, 57% for BOD_5, 62% for sulfate, and 77% for organic N at the flow of 1 m^3/d **(Bulc et al., 2006)**.

The treatment of tannery wastewater is investigated in five HSSF CWs planted with Typha latifolia, Canna Indica, Phragmites australis, Iris pseudacorus, and Stenotaphrum secundatum; however, the sixth unit was unplanted to be the control. Two hydraulic loading rates, specifically 3 and 6 cm/day, were applied to assess the performance of mentioned CWs units. The reductions in the COD and BOD_5 were not exceeded 73 and 58% depended on the organic inlet loading. Typha latifolia and Phragmites australis were the just plants that could establish successfully. Despite the higher removal of organics from influent, no remarkable differences in the efficacy of units can be observed for 17 months **(Calheiros et al., 2007)**.

A system of VF CWs was installed and situated in Turkey. This system consisted of twenty glass tanks to reduce the 11 mg/L influent concentration of BB41 dye under different HRT ranging from 3 to 18 days. The tanks were packed with River sand cultivated with Manchurian wild rice and P. australis. The results showed that the increase in HRT will cause a significant reduction in the dye concentration **(Keskinkan and Göksu, 2007)**.

VF CW can achieve the treatment of wastewater resulting from the textile industry because it represents the ideal choice to satisfy the environmental legislation. The gravel and sand materials were the beds of the VF CWs, which were vegetated with Phragmites australis. For different hydraulic loads, the experimental measurements demonstrated that the COD, color, NH_4-N, and TSS removal efficiencies were equal to 84, 90, 33, and 93% during five months **(Tjaˇsa and Ojstr, 2008)**.

The possibility of two VF pilot scales of wetlands installed in Portugal to remove azo (AO7) dye with a concentration of 700 mg/L and retention time equal to 8 days was investigated. The bed used in these wetlands was gravel, one planted with Phragmites australis and the other utilized as control. Results revealed that COD, TOC, and dye removal efficiencies were equal to 69, 67, and 68%, respectively **(Caetano Davies et al., 2009)**.

Narrow-leaved cattails for removing color and treating textile effluents were utilized. These cattails were set up in a CW model vertically flowing from bottom to top to remove synthetic reactive dye wastewater (SRDW). The SRDW can be removed at 0.8 g (SRDW)/m^2.day with a decolorization percentage of 60% using narrow-leaved cattails **(Nilratnisakorn et al., 2009)**.

The HF vegetated with Phalaris, Phragmites, and local swamp-land plants was employed to provide treatment of trout aquaculture. This system received a flowrate between 26.3 and 72 L/s, and results proved the removal efficiencies of the NH_4-N, NO_3-N, P, BOD, and COD have values within the ranges of 49–87%, 1.6–4.4%, 38–55%, 37–49%, and 24–52% respectively. Relatively higher removal percentages of NH_4-N can be recognized in comparison with other HF wetlands that treated strong wastewater because the influent concentration was within the nitrification capacity of the tested system. It is clear that the reduction efficiency of organic materials was low, and this can be related to low influent concentration to support biological oxidation. Also, low influent concentration could inhibit denitrification within this system **(Sindilariu et al., 2009)**.

The treatment of wastewater containing 50 and 100 mg/L of orange acid (AO7) using up-flow CW with a contact time of 3 and 6 days under an aeration option was examined. The wetlands monitoring was extended from October 2007 to September 2009 at 23±3°C. With the presence of Phragmites australis, the experimental measurements certified that removing NH_4-N and organic material under aerobic conditions is more effective than that removal within non-aerobic wetlands **(Ong et al., 2010)**.

Real textile wastewater was remediated using four reactors of VF CWs installed in India. There are two units, A and B, in each reactor, where B is the storage tank of wastewater supplied to unit A. The remediation process was achieved by infiltration of wastewater through the bed of unit A consisting of soil with bacteria (upper layer) and coconut shavings (bottom layer) in the presence of the Gaillardia pulchella plant. The experimental setup eliminated approximately 74, 70 and 70% of TOC, BOD, and COD, respectively **(Kabra et al., 2013)**.

The treatment efficacy of two large-scale SSF CW pilot plants for an operation period equal to 3 years to treat the municipal sewage was identified. One unit operated as horizontal flow and the second as vertical flow with surface areas equal to 654.5 and 457.6 $m^{2,}$ respectively. The 20 m3/day HL was supplied for each unit, and the temperature was measured within the range of 15-30^{o}C. Canna, Phragmites, and Cyperus were the plants used within the adopted units, and the results signified that the COD, BOD, and TSS could be removed with efficiencies exceeding 90% **(Ella-Abou et al., 2013)**.

BIO_PORE model was built by applying the COMSOL Multiphysics™ platform to accelerate the development of CW models and to understand internal functioning. To take detachment/attachment of particulate in the influent, small changes in the equations of CWs model number 1 (CWM1) were required. Oxygen release and nutrient uptake by the roots of the plants are also simulated. The model was calibrated using measured concentrations of the inlet contaminant, water temperature, and flow rate in the first year of a pilot operation. Simulation for COD and NH_4-N showed a good matching between predicted and experimental data **(Samsó and Garcia, 2013)**.

The treatment of the domestic sewage in the multiple tides of the VF column was investigated. The column was worked under N loading (25–29 g N/m^2.day) at three cycles per day by creating multi-tides in one cycle by filling the bed. This study signified that nitrification could be accomplished by increasing the resting period. Aerobic denitrification could have influenced nitrogen removal in the tidal wetland. Also, the removal of phosphorus was found to be not dependent on the resting periods because physical processes can eliminate this element **(Hu et al., 2014).**

The three units of VF CWs packed with zeolite, sand, and fine gravel (two units cultivated with Cannaidica and Typha Angustifolia while the remaining unit was adopted as control) were utilized to eliminate the acid Yellow 2G E107 dye from contaminated water. The initial dye concentration was 259 mg/L with a loading rate of 0.075 kg/ m^3/day, a flow rate of 1.2 L/day, and a retention period of 3.75 days for an operating time equal to 3 months. For a contact time of three months, the reduction percentage of color for the control unit was 87%, which increased to 98% for other units. Also, results elucidated the mentioned units' ability to remove PO_4-P, NH_4-N, and COD with efficiencies ranging from 43 to 88% **(Yalcuk and Dogdu, 2014)**. The CWM1 bio-kinetic model was used to simulate the experimental results in the batch-fed column. Calibration of model parameters can be implemented based on batch tests because the treatment performance is not influenced by the flow of water **(Pálfy and Langergraber, 2014)**.

Different laboratory-scale of VSSF CW filled with gravel and vegetated with common reed were used to find the effect of operational and design factors on the overall water quality, especially after diesel spillage. The effects of organic and hydraulic loading, grain size, and aeration period were investigated. The Wang-Scholz simulation model was upgraded to predict hydrocarbon removal in the experimental wetland filters. All wetland units have relatively high removal efficiency for major water quality parameters regardless of filter set-up before the diesel spill. Upgraded Wang-Scholz model results indicate relatively good for the period before hydrocarbon contamination and variable after the contamination **(Al-Isawi et al., 2015)**.

Horizontal CWs packed with gravels and biochar beds of dimensions (1 m × 0.33 m × 0.3 m) were prepared and planted with *Canna* species. Artificial wastewater was allowed to pass through mentioned beds for a 3-day retention time and flow rate of 1.2 × 10−7 m3/sec. The experimental measurements revealed that the CW of biochar was more efficient from wetlands with gravels alone, with removal efficiencies of 58.3% NH_3, 58.3% TN, 92% NO_3-N, 79.5% TP, and 67.7% PO_4 and 91.3% COD **(Gupta et al., 2016)**.

The efficiency of VSSF CW for treating sewage was investigated in Egypt through the period extended for 8 months under different conditions: the presence and absence of common reeds, gravel, or vermiculite for packed bed, and type of sewage loading (batch or continuous). The treatment efficiencies of BOD, COD, TSS, NH_4, and TP were 37, 29, 42, 26 and 17% for unplanted beds; however, these values have increased to 84, 75, 75, 32 and 22% for planted beds, respectively **(Abdelhakeem et al., 2016)**.

The stability of hybrid CWs was provided when comparing different configurations regarding mass removal and treatment efficiency for adopted contaminants. Measurements were conducted at multistage CWs in Poland, and these wetlands are composed of at least two beds; HF and VF. The evaluation was concentrated on the performance of HF+VF versus VF+HF arrangement, where the influent has the same quality. Results proved that the hybrid CWs could be removed from organic materials and total nitrogen with values not exceeding 90 and 60%, respectively, where the configuration VF+HF can lead to better final effluent quality **(Gajewska et al., 2017)**.

The CWs were utilized to treat synthetic wastewater contaminated with Basic Red 46 (BR46) and Acid Blue 113 (AB113). The wastewater was passed through laboratory-scale VF CWs systems with P. australis. The highest and lowest concentrations for adopted dyes, specifically 208 and 7 mg/L, were utilized with corresponding hydraulic contact times of 96 and 48 h. For low concentration, the unplanted CWs achieve the reduction performance for dye removal with significance ($\rho < 0.05$) compared with planted units. The CWs with longer

contact time were significantly ($\rho < 0.05$) better than the units operated with shorter time for a high concentration of AB113 and BR46 through the achieved reduction in the COD, dye, and color **(Hussein and Scholz, 2017)**.
The wastewater from the batik industry using hybrid CWs planted with Canna Indica was treated. This industry considers one of the Indonesian economic drivers. Batik industry frequently discharged its effluent without any prior treatment, thus endangering the ambient. The parameters like COD, TSS, and oil and grease (FOG) were monitored after 3, 5, and 7 days of HRT. The measurements indicated that the applied system could gain the FOG and COD removal percentages on day 3 at 89.53 and 89.61%, respectively, while the removal of TSS on day 5 at 98.74% **(Rahmadyanti and Audina, 2020)**.
Remediating Congo red dye wastewater using planted and unplanted VSSF CWs was achieved. Four containers were manufactured and packed with a bed of sewage sludge to treat the dye's initial concentration (10-40 mg/L) with an HRT of (1–5 days). The densities and heights of Typha domingensis and P. australis have increased from 5 plant/unit and 0.15 m at the beginning of the plantation to 59 plant/unit and ≤1.65 m, respectively, after 136 days. Results signified that the increase of operation duration with reduce of inlet Congo red concentration could associate with a clear increment in the removal percentages of dye and COD, which are equal to 96.5 and 46%, respectively, after a 5-day treatment period for 10 mg/L inlet dye concentration **(Faisal and Badah, 2021).** This study used Phragmites australis with a free surface batch system to estimate its ability to remediate total petroleum hydrocarbons (TPH) and chemical oxygen demand (COD) from Al-Daura refinery wastewater. The system operated in semi-batch. Thus, new wastewater was weekly added to the plant for 42 days. The results showed high removal percentages (98%) for TPH and (62.3%) for COD. Additionally, Phragmites australis biomass increased significantly during the experiment period, with a 60% increase in wet weight **(Fadhil and Al-Baldawi, 2019).**

13. CONCLUSIONS

Various types of domestic, commercial, and industrial wastewater with a wide range of properties are treated using the available configurations of CWs to obtain effluents that satisfy acceptable environmental regulations. A summary of current knowledge on the principles, components, mechanisms, and benefits of such technology can be included; 1) The influences of detention time, hydraulic loading, temperature, wastewater recycling, aeration, and type of plant on the performance of VF, HF and hybrid systems in the treatment of municipal wastewater were investigated; 2) the possibility of applying all configurations of CWs for treating industrial wastewater contaminated with heavy metals and/or organic pollutants have studied, 3) It is highly recommended to adopt the CW systems for increasing green land areas and providing new habitat for a variety species. They can be placed near entrances, as well as be used as green belts around the cities.

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