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Sustainable Treatment of Wastewater with the Help of Constructed Wetlands

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ABSTRACT

A wetland is a unique and distinct ecosystem that is flooded by water, either permanently or seasonally, where oxygen-free processes prevail, and the primary distinctive factor of wetlands from other landforms or water bodies is the occurrence of adaptive vegetation of aquatic plants, characteristic to the unique hydric soil. A constructed wetland is an artificial shallow basin filled with substrate, usually soil or gravel, and planted with vegetation that has tolerance to saturated conditions. As much as the use of constructed wetland has been recommended in the treatment of various forms of wastewater, the system efficiency is a factor of very many natural and artificial factors, with the emerging pollutants and contaminants such as resistant genes being the most complicated contaminants to eliminate through the system. Indeed, the emerging pollutants in forms of antibiotic resistant genes (ARGs) have remained prevalent in aquatic environments such as wetlands that receive ARG-loaded sewage. Therefore, this chapter covers a discussion on constructed wetlands in wastewater treatment and challenges of emerging contaminants, such as resistant genes filtration and reloading mechanisms, and provides recommendation for the proper handling and removal of such pollutants from the wetlands' functional system.

KEYWORDS: *wetlands, sustainable, ecosystem, wastewater, contaminants, pollutants, substrate*

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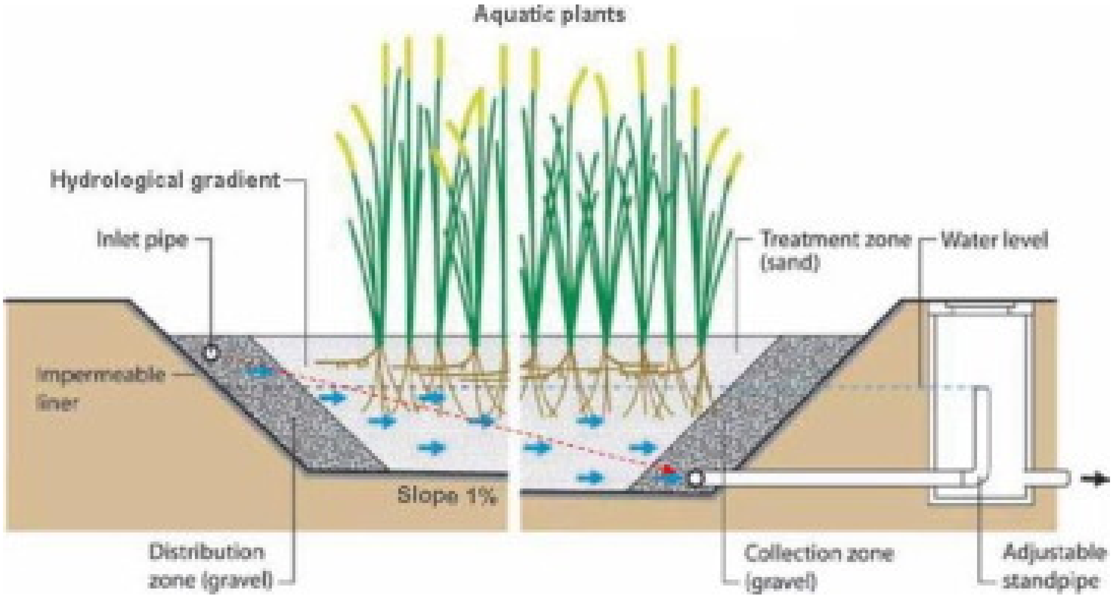
INTRODUCTION

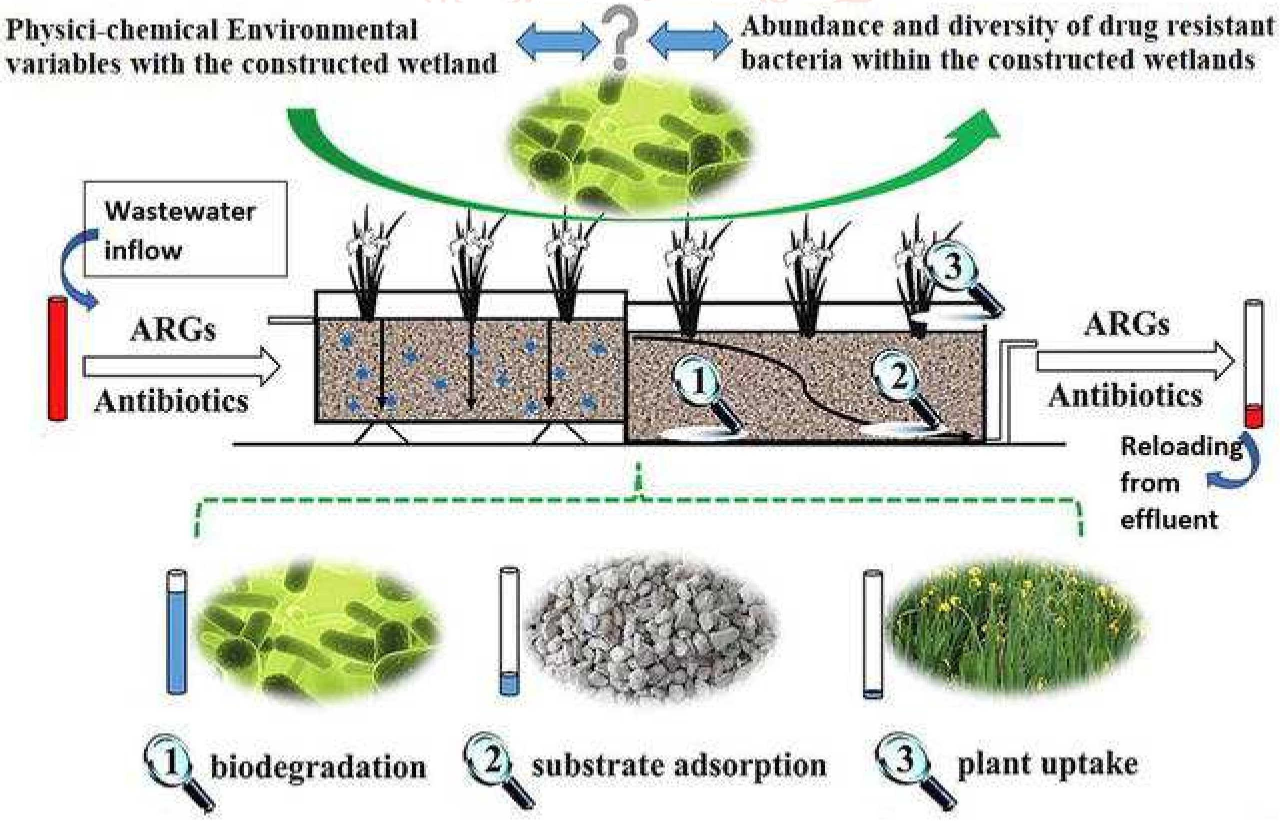
Wetland is a unique and distinct ecosystem that is flooded by water, either permanently or seasonally, where oxygen-free processes prevail, and the primary distinctive factor of wetlands from other landforms or water bodies is the occurrence of adaptive vegetation of aquatic plants, characteristic to the unique hydric soil [1, 2]. The modified form of wetland is termed "constructed wetland." Constructed wetlands for water treatment are complex, integrated systems of water, plants, animals, microorganisms, and the environment [3, 4]. Wetlands play a number of functions, including water purification, water storage, processing and recycling of carbon and other micro and macro nutrients, stabilization of shorelines, and support of plants and animals. While wetlands are generally reliable, self-adjusting systems, an understanding of how natural wetlands are structured and how they function greatly increases the likelihood of successfully constructing a wetland treatment system [5, 6].

The cleansing of water has always occurred through natural processes as the water flows through rivers, lakes, streams, and wetlands, and in the last several decades, systems have been constructed to use some of these processes for water quality improvement [7].



Wetlands are now highly preferred as systems for improving the quality of point and nonpoint sources of water pollution, including storm water runoff, domestic wastewater, agricultural wastewater, as well as coal mine drainage [4]. To enhance sustainability in wastewater management, the use of constructed wetlands has been applied in the treatment of different forms of wastes. Artificially created wetlands have been successful in the treatment of petroleum refinery wastes, wastes from sugar factory, leachates from landfills and composts, wastes from aquaculture systems, wastes from pulp and paper mills, and wastes that emanate from slaughter houses, textile mills, and plants that process sea food. Under the management of these wastes, the constructed wetlands can serve as the sole treatment or may be part of an integrated wastewater treatment system [8].

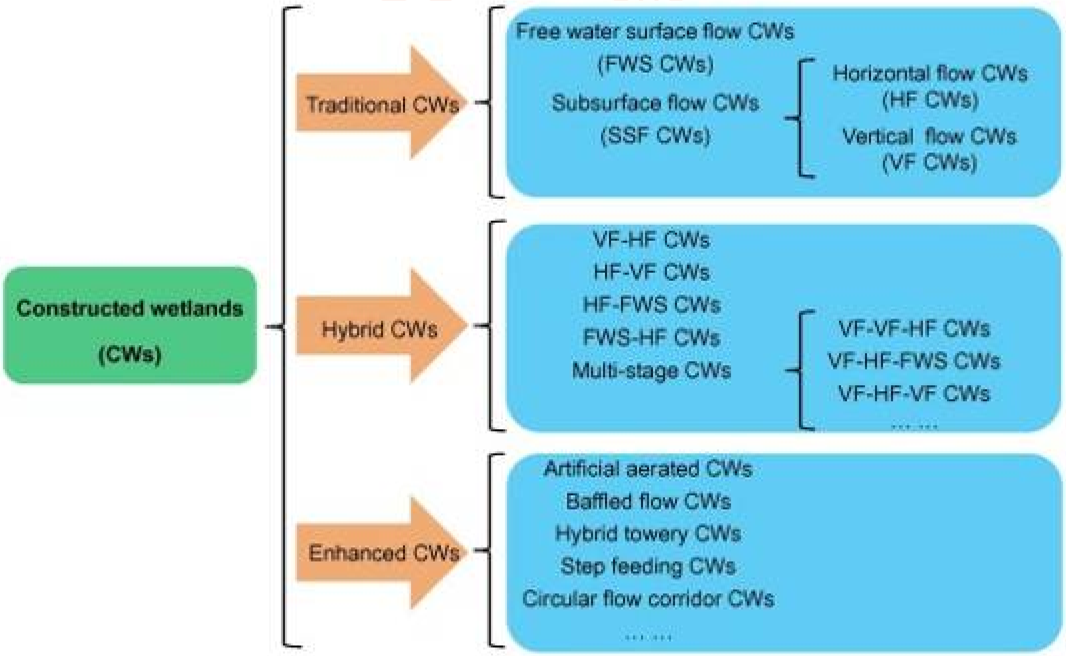
Antimicrobial resistance (AMR) is defined as the ability of a microbe to resist the effects of medication that was once successful and efficient in treating the microbe [9]. The term antibiotic resistance (ABR) is a subset of AMR, as it applies only to bacteria becoming resistant to antibiotics. The AR phenotypes can arise within a microorganism through the lateral and horizontal gene transfers and mutation. The mutations of the chromosomal DNA alter the existing bacterial proteins, through transformation, resulting in the creation of mosaic proteins and/or as a result of the transfer and acquisition of new genetic material between bacteria of the same or different species or genera [10]. The emerging pollutants in forms of antibiotic resistance genes (ARGs) have remained prevalent in aquatic environments such as wetlands that receive ARG-loaded sewage [11].



As much as the use of constructed wetland has been recommended in the treatment of various forms of wastewater, the system efficiency is a factor of very many natural and artificial factors, with the emerging pollutants and contaminants such as resistant genes being the most complicated contaminants to eliminate through the system [11, 12]. Moreover, some studies have reported constructed wetlands as reservoirs to various forms of resistant genes, which trap them and release them to other aquatic systems, hence contributing to their higher concentration in streams, rivers, or lakes [13]. Numerous suggestions have been provided to improve wetland's functional effect, efficiency, and predictability and provide a proper ecosystem management [6, 7]. This chapter covers a discussion on the constructed wetlands in wastewater treatment and the challenges of emerging related contaminants, such as resistant genes, and provides recommendation for the proper handling and removal of such wastes from the wetland's functional system.

Discussion

Wetlands are ecotones/transitional areas between land and water, with indistinct boundaries between the wetland area and uplands or deep water [14]. The definition expansion of the term wetland covers a broad range of systems that range from marshes, bogs, swamps, wet meadows, tidal wetlands, floodplains, and ribbon (riparian) zones along stream channels. However, all wetlands, whether they are natural or artificial, freshwater, or salty, pose a single characteristic or numerous characteristics, and they occur within the surface or near-surface water, whether they are permanently or temporarily submerged under water [15]. In most wetlands, hydrologic conditions are such that the substrate is saturated long enough during the growing season, a mechanism that creates oxygen-poor conditions in the substrate, limiting the vegetation to those species that are adapted to low-oxygen environments [16].



Wetlands provide a number of functions and benefits. Wetland functions are inherent processes occurring in wetlands; wetland values are the attributes of wetlands that society perceives as beneficial [17]. The wetland hydrology is generally one of slow flows with either shallow waters or saturated substrates, which allows sediments and other pollutants, including emerging contaminants to settle as the water passes through the wetland system. The occurrence of slow flows provides prolonged contact times between the water and the surfaces within the wetland [15]. The wetland treatment mechanisms are anchored on the complex mass of organic and inorganic materials, with diverse opportunities for gas/water interchanges, which foster a diverse community of microorganisms that break down or transform a wide variety of substances [7]. Within the wetland's ecosystems, there are dense growths of vascular plants adapted to saturated conditions, which slow the water, create microenvironments within the water column, and provide attachment sites for the microbial communities as well as other contaminants. The litter that accumulates as plants die back in the fall creates additional material and exchange sites and provides a source of carbon, nitrogen, and phosphorous to fuel microbial processes [18].

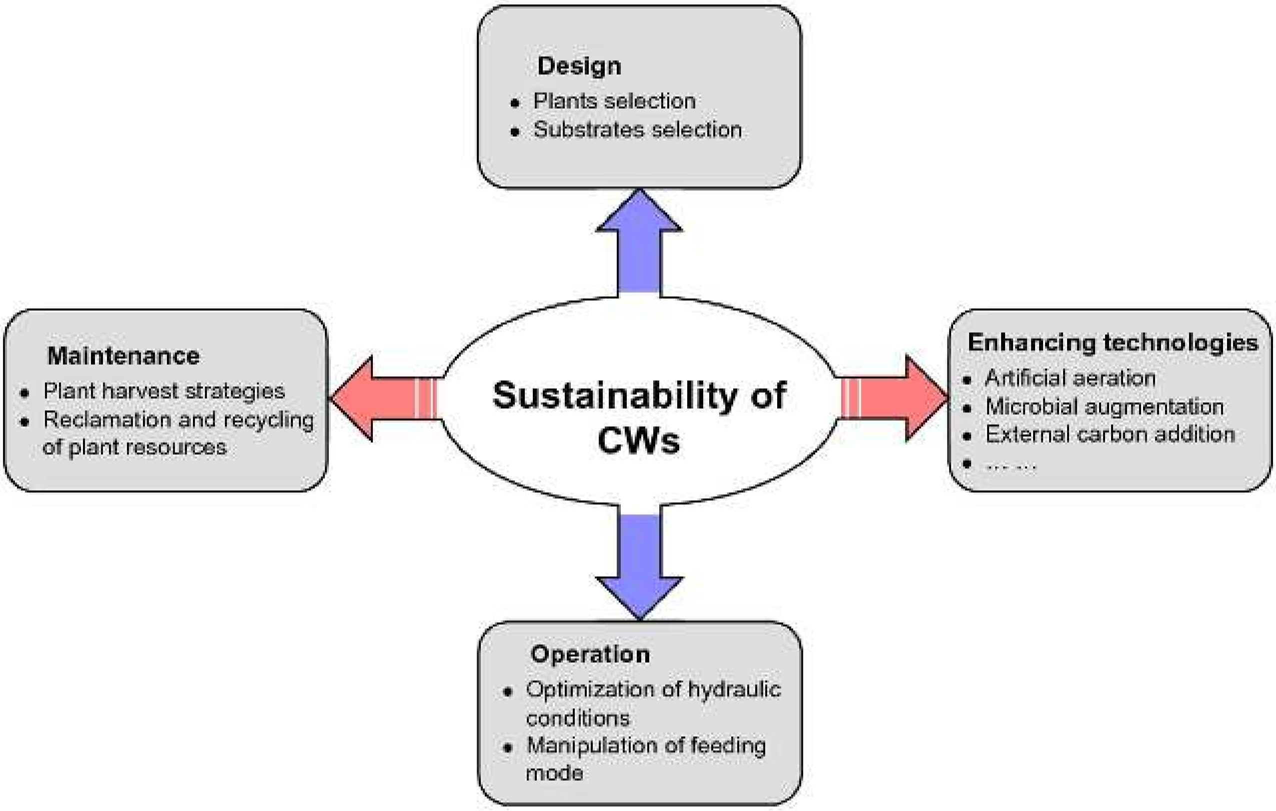
Even though, not all wetlands can perform all functions and values, majority of them provide several benefits. When subjected to appropriate ecological management without any threats, majority of wetlands can provide the following:

1. Water quality services
2. Flood storage services under excessive precipitation and the desynchronization of storm
3. Nutrients and other materials cycling services
4. Habitat for fish and wildlife
5. Services for passive recreation, such as bird watching and photography
6. Services for active recreation, such as hunting education and research
7. Services for esthetics and landscape enhance merit

A constructed wetland is an artificial shallow basin filled with substrate, usually soil or gravel, and planted with vegetation that has tolerance to saturated conditions. Water is then directed into the system from one end and flows over the surface (surface flow) or through the substrate (subsurface flow) and gets discharged from the other end at the lower point through a weir or other structure, which controls the depth of the water in the wetland [11]. Several forms of constructed wetlands have been introduced, including surface flow wetlands, subsurface flow wetlands, and hybrid systems that integrate surface and subsurface flow wetland types [6, 19]. Constructed wetland systems can also be combined with conventional treatment technologies to provide higher treatment efficiency [8]. The choice of constructed wetland types depends on the existing environmental conditions and how appropriate they are for domestic wastewater, agricultural wastewater, coal mine drainage, and stormwater [6].

Constructed wetlands have been widely used in the treatment of primary or secondary domestic sewage effluents, and others have been used to treat domestic wastewater and have also been modeled to handle high organic loads associated with agriculture or domestic wastewater [5]. A large number of constructed wetlands have also been built to treat drainage from active and abandoned coal mines [20]. The constructed wetland technology has recently been used in the control and management of stormwater flows, and its application in reducing the impacts by stormwater floods within urban areas is expanding globally [21]. The constructed wetland technology is not only preferred in stormwater flow control but also in the treatment of wastewater, and its preference is based on its low cost, low energy requirement, and need for minimal operational attention and skills. Due to its numerous merits and high sustainability potential, there is an increasing extensive research on its practical application to expand the knowledge on its operation and to provide more insight on its appropriate design, performance, operation, and maintenance for optimum environmental benefits. Even though the constructed wetlands are sturdy and effective systems, their performance depends on the periodic improvements to handle emerging contaminants such as antibiotic and antibacterial resistant genes, and for them to remain effective, they must be carefully designed, constructed, operated, and maintained [11, 12].

Implications



Constructed wetland is a system that puts together different units that work together to ensure that its intended purpose is achieved. Constructed wetland systems entail a properly designed and constructed basin that holds water, a substrate that provides filtration pathways, habitat/growth media for the needed organisms, and also communities of microbes and aquatic invertebrates, which in most cases develop naturally. Most importantly, constructed wetlands also hold vascular plants whose nature depends on the intended purification role and efficiency. The efficiency of the constructed wetlands in waste treatment depends on the interaction and maintenance of these components [22].

In a constructed wetland system, natural geochemical and biological processes within a wetland realm are involved in the treatment of metals, explosives, and other contaminants that exist within the water. Normally, there are three primary components in a constructed wetland. Constructed wetland has an impermeable layer (generally clay). It also has a gravel layer that acts as a substrate needed for the provision of nutrients and support to the root zone. It also has an above-surface vegetation zone [16]. The impermeable layer within the constructed wetland system prevents infiltration of wastes down into underground aquifers. The gravel layer and root zone comprise of a layer where water flows and bioremediation and denitrification occur. The above-ground vegetative layer contains the well-adopted plant material. Within the wetlands, both the aerobic and anaerobic processes occur, and these can be divided into separate cells [5, 16]. Groundwater can be made to flow through pumping or naturally by gravity through the wetland. Within the anaerobic cells, plants and other natural microbes are involved in the degradation of the contaminant. The aerobic cell performs the work of further improving the water quality through continued exposure to the plants and the movement of water between cell compartments. The use of straw, manure, or compost with little or no soil substrate has been beneficial in the wetlands constructed primarily for the removal of metals. However, for wetlands constructed to treat explosives-contaminated water, certain plant species are used to enhance the degradation through a process termed phytoremediation [23].

Wetlands are formed on substrates that are fully or partially submerged in water, where a relatively impermeable subsurface layer prevents the surface water from seeping into the ground [1, 2]. These conditions can be created with few modifications to form a constructed wetland. A constructed wetland can be built almost anywhere in the landscape by shaping the land surface to collect the surface water and by sealing the basin to retain the water [7]. Hydrology that enhances the linking of all the functions in a wetland system stands as the most important design factor to be considered in constructed wetlands, as it is often the primary factor in the success or failure of most constructed wetlands. Therefore, planning and putting up of constructed wetlands require the contribution of a qualified hydrologist to ensure that all the hydrological requirements and conditions are taken care of [24]. Even though the hydrology of most constructed wetlands is very much similar to the other surface and near-surface water, it does differ in several important respects. Small changes in hydrology can have fairly significant effects on a wetland's functionality and its treatment effectiveness and efficiency. Indeed, due to the large surface area of the water and its shallow depth, a wetland system interacts strongly with the atmosphere through rainfall and evapotranspiration. This (the combined loss of water by evaporation from the water surface and loss through transpiration by plants) and the density of the vegetation of a wetland strongly affect the constructed wetlands' hydrology. This can be experienced through the obstruction of water flow paths as the water finds its sinuous way through the network of stems, leaves, roots, and rhizomes, and it can also occur through the blockage of exposure to wind and sun [7, 24, 25]. Water always acts as a vehicle for delivering the pollutants to the system and also for discharging the untapped pollutants away from the system [24].

Results

Substrates for constructed wetlands can come in the form of sediment or litter. Substrates used to construct wetlands include soil, sand, gravel, rock, and organic materials such as compost [26]. Due to low water velocities and high productivity typical of wetlands, the sediment and litter accumulation occurs within the wetlands. The substrates, sediments, and litter have numerous functions that are beneficial to the efficiency of the constructed wetlands. They provide support to many of the living organisms in wetlands, and the substrate permeability also affects the movement of water through the wetland and provides numerous chemical and biological processes, many of which are microbial in nature and also enhance the transformation of pollutants within the substrates. The substrates also provide storage for many contaminants, and the accumulation of litter increases the amount of organic matter in the wetland, which provides sites for material exchange and microbial attachment. Through this process, carbon source is realized as well as the energy source that drives some of the important biological reactions in wetlands.

Flooding of the constructed wetlands with water has a contribution in its functional mechanism. The physical and chemical characteristics of soils and other substrates are altered when they are wholly or partially under water. For example, under saturated substrate, the water replaces the atmospheric gases within the pore spaces and the microbial-driven metabolism results in the consumption of the available oxygen. Therefore, since oxygen is consumed more rapidly than it can be replaced by diffusion from the atmosphere, the substrates change to anoxic condition (without oxygen). Such conditions become significant in the removal of pollutants such as nitrogen and metals. However, substrates can also act as reservoirs for most contaminants, with high concentration of emerging contaminants such as resistant genes being detected in the constructed wetland substrates [27, 28].

Constructed wetlands can work with both the vascular plants (the higher plants) and nonvascular plants (algae), and the photosynthesis process by algae increases the dissolved oxygen content of the water which in turn affects nutrients and metals [18, 29]. Constructed wetlands also attract large organisms such as birds which can feed on contaminants. Additionally, they form attachment surfaces for other protozoans and other microorganisms such as zooplanktons, phytoplanktons, and bacterioplanktons which also aid in the elimination of pollutants and contaminants [30, 31]. Vegetation acts as the main trapping and retention points for most contaminants. Studies have continued to detect a high concentration of emerging contaminants such as resistant genes within the root systems of most constructed wetland vegetations [11, 32].

Performance and functions

Constructed wetlands' performance is also a factor of other life-forms. Organisms within the wetlands include microorganisms and other larger animals. The regulation functions by the microorganisms and their metabolism processes are the fundamental functions of the wetlands systems [33]. The microorganisms are varied in species and possess the required adaptions to drive the functions of the wetland systems. The known significant microorganisms include bacteria, yeasts, fungi, protozoa, and rind algae. The biomass generated from these microbes (microbial biomass) forms a major useful sink for organic carbon and many nutrients. Additionally, the microbial activities also transform a great number of organic and inorganic substances into innocuous or insoluble substances as well as alter the reduction/oxidation (redox) conditions of the substrate, and thus not only affect the processing capacity of the wetland but also enhance the recycling of nutrients. Some microbial transformation processes are aerobic as they require free oxygen to occur, while others are anaerobic as they occur under the absence of free oxygen. However, most of the bacterial species are also facultative anaerobes in nature. These groups are capable of functioning under the constructed wetland conditions of either aerobic or anaerobic in response to changing environmental conditions [6, 34].

The level of water within a constructed system is crucial to the microbial activities, and microbial populations undergo adjustments to changes in the water delivered to them. Populations of microbes can rapidly expand under the condition of suitable energy-containing materials. However, when environmental conditions become unsuitable, many microorganisms become dormant and can remain dormant for years [35]. The microbial community of a constructed wetland can be affected by toxic substances, such as pesticides and heavy metals, and care must be taken to prevent such chemicals from being introduced at damaging concentrations. The biodiversity with the constructed wetlands is rich, and this is based on the favorable habitat that the system provides to different forms of organisms, which range from animals to plants, including invertebrates and vertebrates. The invertebrate animals, which include insects and worms, contribute to the treatment process by actively fragmenting detritus and consuming organic matter [36]. Additionally, the larvae of many insects are also aquatic and they undertake the consumption of a significant amount of material during their larval stages, which may last for several years in most insect species. The invertebrates also perform a number of ecological roles; for example, dragonfly nymphs have been confirmed to be important predators of mosquito larvae which results in biocontrol of malaria in most waterlogged areas. Despite invertebrates being the most important animals as far as water quality improvement is concerned, constructed wetlands also harbor a variety of amphibians, turtles, birds, and mammals, all of which are important in the systems' ecological balancing [37].

Basic details

The mechanisms that are available to improve water quality within a constructed wetland system are numerous and often interrelated. The mechanisms involve the settling of suspended particulate matter; the filtration and chemical precipitation through contact of the water with the substrate and litter; chemical transformation; adsorption and ion exchange on the surfaces of plants, substrate, sediment, and litter; the breakdown and transformation of pollutants by microorganisms and plants uptake; and transformation of nutrients by microorganisms and plants as well as the predation and natural die-off of pathogens [36]. The removal can be undertaken biologically through microbiological degradation through catabolism and anabolism, protozoic predation and digestion, and through plant uptake and storage; chemically through adsorption (ionic and covalent) oxidation, reduction, and UV degradation and physically through filtration and settlement, which filters some materials and degrades others [38, 39, 40].

Constructed wetland treatment technology incorporates the principal components of wetland ecosystems that promote degradation and control of contaminants by plants, degradation by microbial activity, and increased sorption, filtering, and precipitation [38, 39, 40]. The treatment need dictates the nature of technology required and requires proper selection of designs, such as surface or subsurface flow, single or multiple cells, and parallel or series flow. Putting up of constructed wetland systems are sometimes part of a treatment train that integrates processes in series such as settling ponds, oil/water separators, and physical/chemical treatment methods. The removal mechanisms within the constructed wetlands can act uniquely, sequentially, or simultaneously on each contaminant group or species [3, 4]. For instance, the volatile organic compounds (VOCs) in contaminated groundwater are primarily eliminated through the integrative physical mechanism of diffusion-volatilization. Further to this, mechanisms such as adsorption to suspended matter, photochemical oxidation, and biological degradation may also play a role. Within a constructed wetland treatment system, physical removal mechanisms of contaminants include settling, sedimentation, and volatilization. Gravitational settling is responsible for most of the removal of suspended solids. The most effective treatment wetlands are those that foster these mechanisms.

Merits and demerits of constructed wetlands in waste handling

The long-term effectiveness of constructed wetlands to contain or treat some contaminants is not well known. Wetland aging may contribute to a decrease in contaminant removal rates over time. However, constructed wetlands are a cost-effective and technically feasible approach to treating wastewater and runoff for several reasons [41].

Constructed wetlands' demerits outweigh the merits. Some of the merits are that they can be less expensive and more affordable to build than other forms of treatments, their cost of operation and maintenance (required supplies and energy) are low, and the operation and maintenance only require periodic and not continuous on-site labor. Furthermore, the constructed wetlands are able to tolerate fluctuations in flow, they sustainably facilitate water recycling and reuse, they provide favorable habitat for many wetland organisms, and the system can be built to fit harmoniously into the landscape. Constructed wetlands have the ability to provide numerous benefits in addition to water quality improvement, such as wildlife habitat that supports tourism and other sporting, and they enhance the esthetic enhancement of open spaces. Therefore, due to all the above economic, ecological, and esthetic benefits, constructed wetlands are environmentally sensitive treatment approaches that are viewed with favor by the general public [42].

Conclusions

The use of constructed wetlands is also subject to limitations that are associated with the use and putting up of the system. Compared to conventional wastewater treatment systems, constructed wetlands generally require larger land areas. Even though wetland treatment may be economical relative to other options, this only applies to where land is available and affordable. The constructed wetland's performance efficiency may be less consistent as compared to the conventional treatment. The treatment efficiency of constructed wetlands may vary; this variation may be seasonal in response to changing environmental conditions, including rainfall and drought or spatial in relation to the existing weather conditions in different places. While the average performance over the year may be acceptable, but due to such fluctuations in performance efficiency, wetland treatment cannot be relied upon if the effluent quality must meet stringent discharge standards at all times. The biological components are always sensitive to toxic chemicals, such as ammonia, and other pesticides that are periodically flushed or surged by the flowing water, and this may temporarily reduce treatment effectiveness and reduce the efficiency. For proper survival and improved efficiency, constructed wetlands also require a minimum amount of water. While wetlands can tolerate temporary drawdowns, they cannot withstand complete drying and some plants in it can also not tolerate complete submergence [1]. The use of constructed wetlands for wastewater treatment and stormwater control is a fairly recent development. There is yet no consensus on the optimal design of wetland systems, nor is there much information on their long-term performance.

Furthermore, its ability and potential to eliminate emerging contaminants such as resistant genes have not been fully realized [32].

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