Applications of constructed wetlands and hydroponic systems in phytoremediation of wastewater

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Abstract. Increase in population and urbanisation alongside demands from agricultural sector towards meeting fresh produce needs of the growing population has put severe pressure on the available natural water sources all over the world. Thus, water is undoubtedly the most contemporary crucial resources in the world. Aquatic weed plants are generally seen as a global threat to humans and aquatic ecosystem as they cannot be wholly eliminated easily. Still, various researchers and investigations have shown that they are instrumental in the field of wastewater phytoremediation, either in constructed wetlands, open ponds or hydroponic systems in an eco-friendly and economical manner with little or no sludge waste. In view of the increasing search for an alternative source of a sustainable method for wastewater reclamation, this study presents a concise review of relevant literatures on the roles of constructed wetlands and hydroponic systems in phytoremediation of wastewater. Also in the course of this study, the authors discovered that constructed wetlands and hydroponic systems have proven to be productive in remediating an array of water quality problems, with merits over the regular wetlands and conventional methods. Nonetheless, these methods are endowed with drawbacks such as inconsistency in the absorption of contaminants, large area space requirement, over dependency on environmental conditions and energy requirement. However, we suggest the use of engineered hybrid to improve its efficiency in wastewater treatment and bioenergy generation. In the case of hydroponic systems, an alternative sustainable solar energy or devices can be used to power the systems to obtain effective results at a low cost. Additionally, further studies can be employed in the use of phytoremediation technique for synchronous remediation of wastewater and production of biomass on industrial scale.

1. Introduction
The increase in population and urbanisation alongside demands from agricultural sector towards meeting fresh produce needs of the growing population has put severe pressure on the available natural water sources all over the world [1]. It has been estimated that throughout the year approximately 500
million people dwell in environments of inadequate water supply, as well as more than 14 billion people around the world survive on insufficient water every year [2]. Thus, water is undoubtedly the most contemporary crucial resources in the world. Hence, the act of water preservation and developing different strategies through which challenges of water scarcity are met is considered a global task. In this regard, water recycling through biological procedures such as phytoremediation is perceived as a workable way to supplement freshwater. In actual sense, current and future water shortages could possibly be addressed by the application of this procedure [3]. Treated wastewater from domestic sewage treatment plants is considered healthy for domestic and agricultural use and has been found to be cost-effective and promising for enhancing supplies of fresh water [4,5]. Phytoremediation is a developing technology employed to remove, degrade, metabolise, or immobilise a wide range of contaminants from the air, soil or water through the exploits of potentials of selected plant species like aquatic plants [6]. Aquatic weed plants are generally seen as a global threat to humans and aquatic ecosystem as they cannot be wholly eliminated easily. Still, various researchers and investigations have shown that they are instrumental in the field of wastewater phytoremediation, either in constructed wetlands (CWs), open ponds or hydroponic systems in an eco-friendly and economical manner with little or no sludge waste.

Aquatic plants (macrophytes) have been reported to absorb superfluous impurities (heavy metals, inorganic and organic pollutants, pharmaceutical, radioactive elements, and nanoparticles wastes) found in municipal and industrial sewage sources either at secondary or tertiary stage of water treatment through phytostabilisation, phytovolatilisation, phytodegradation, rhizofiltration, phytotransformation or phytoextraction. Thereby, making treated wastewater to meet up with the International Standard Requirements in different applications. Despite the potentials of this technology in wastewater reclamation, phytoremediation is limited to shallow area and depth occupied by plant roots and it is absolutely impossible to prevent the leaching of contaminants into groundwater with the application of plant-based systems of remediation. The survival of plants is affected by the toxic substance from contaminated soil and the general condition of the soil. Plant-based phytoremediation technologies have gained recognition over the years and are considered to be effective methods for cleaning up soil and water pollutants. Different plant species have exhibited great potential as agents of phytoremediation. These plants include several monocots and dicots, grasses and trees [7].

Therefore, due to the increasing search for an alternative source of a sustainable method for wastewater reclamation, this study presents a comprehensive overview of the related literature on the role of built wetland and hydroponic systems in wastewater bioremediation. In this regard, recent research articles published between 2018 and 2020 were used to evaluate the efficiency of advanced wetland and hydroponic systems in the treatment of urban wastewater through the cultivation of selected plant species. Accordingly, this review discusses the similarities and advantages of constructed wetland over the hydroponic system and vice versa.

This paper is structured as follows: section 2 discussed the overview of constructed wetlands in phytoremediation techniques. Subsection 2.1 briefly describes the advantages of constructed wetlands over hydroponic systems. Subsection 2.2 examined the applications of constructed wetlands in wastewater remediation. Section 3 present an overview of hydroponic systems in wastewater treatment. Subsection 3.1 illustrates the advantages of hydroponic systems of wastewater over constructed wetlands. Subsection 3.2 presents the applications of hydroponic systems in wastewater bioremediation.

2. Overview of constructed wetland in phytoremediation

The efficiency of wetlands in reclamation of wastewater is primarily determined by the type of aquatic plant species, influent feeding mode, hydrology, surface loading rate, substrate, temperature and availability of microorganisms. A constructed wetland (CWs) is a man-made swamp, developed and built in a manner to allow the applications of natural ecosystems involving vegetation, microbial assemblages, and soils in order to improve the reclamation of wastewater [8]. Typically, it comprised of series of connected rectangular basins encircled by sand, concrete, rocks and other solid materials. Constructed wetlands are generally classified into subsurface and surface flow wetlands. Subsurface systems are more common in Europe and are efficient than the surface flow systems, but is
significantly costly compared to surface flow wetlands. While surface flow wetlands involve vast land than subsurface wetlands in pollution reduction, but they are easier, cheaper to design and build. However, surface flow wetlands are most common in North America, particularly in the United States [9]. CWs is considered as efficient eco-technology capable of removing suspended solids and organic materials through the use of physical, chemical and biological processes for various wastewater treatments [10]. CWs have been reliably engaged for reclamation of wastewater in either secondary or tertiary stage of wastewater treatment [11]. Several macrophytes have been used in a constructed wetland for phytoremediation processes. These plants can be categorised into emergent plants (C. rostrata, A. calamus L., S. lacusris L., P. australis, T. latifolia L., Eleocharis spp., Juncus spp. and Iriss spp.), free-floating macrophytes (M. quadrifolia L., N. peltata, T. bispinosa, N. lutea L., and N. odorata), and submerged plants (P. crispus L., C. demersum L., H. verticillata (L.f.), M. spicatum L., and V. natans) [12,13].

Moreover, environmental factors such as dissolved oxygen (DO), aerobic and anaerobic conditions and nutrients from different sewage sources can be maintained in constructed wetland [14]. However, CWs have proven to be productive for reclamation of different type of wastewater, with merits over the traditional wetlands, as well as demerits, such as the inconsistency of CWs as a result of fluctuations in the environmental changes when compared to conventional treatments. The biological components are susceptible to harmful substances, and leaching of contaminants in water flow may hinder effectiveness of treatment processes. These limitations of CWs can be addressed through an engineered wetland or using combinations of various types of CW designs within a more controlled way to take advantage of ordinary CWs [8,15].

2.1. Advantages of constructed wetland over hydroponic systems in wastewater treatment

CWs methods is regarded an economically driven technique that has been used in treatment of landfill leachate, agricultural, municipal and industrial wastewater from secondary to tertiary treatment stage [16]. While hydroponic methods are known to operate a shallow system of wastewater treatment composed of low strength contaminants usually from agricultural and municipal effluent discharge. The idea of CWs is popularly used for rural communities where decentralised approach for bioremediation of wastewater is adequately favoured. Whereas, in most cases, hydroponic systems are employed in lab-scale or pilot-scale treatment of wastewater under greenhouse environment. The efficiency of CWs in wastewater reclamation depends on environmental or seasonal changes, which makes its low energy requirement method. On the other hand, hydroponic systems require a stable source of energy. Additionally, CWs methods go beyond the treatment of wastewater to provide natural habitat and migratory wildlife [17]. On the contrary, hydroponic systems are limited to wastewater treatment and cultivation of crops. In addition, the aesthetics significance of sub-urban and rural areas is greatly improved by CWs [18], as it can be used in habitat formation, flood control and wastewater decontamination [8].

2.2. Applications of constructed wetlands in wastewater remediation

In order to meet up with accepted water quality reuse standards, effectiveness of CWs in degrading organics and suspended solids from wastewater systems could be improved by combining different types of constructed wetlands [15]. However, reports from recent studies have revealed the application of engineered hybrid CW systems for bioremediation of wastewater. Ali et al. [19] assessed the continuous variable flow of hybrid CWs designed for reclamation of domestic wastewater. In the study, two systems of anaerobic baffled reactor coupled with a saturated vertical subsurface flow (VSSF) and horizontal subsurface flow (HSSF) CWs was used. The findings from the study indicates that maximum reduction of 80% and 78% for chemical oxygen (COD), 81% and 82% for biological oxygen demand (BOD), 63% and 69% for total Kjeldahl nitrogen (TKN), 79% and 89% for total suspended solids (TSS) from the wastewater samples was achieved in VSSF and HSSF CWs, respectively. Likewise, García-Ávila [20] conducted a comparative analysis of cultivated P. australis and C. papyrus in VSSF-CWs for phytoremediation of wastewater. The phytoremediation technique efficiency in conjunction with the physical, chemical and biological factors were examined for three months. The results obtained showed that removal efficiency of ammoniacal nitrogen (69.69%), BOD
(69.87%), COD (80.69%), total phosphorous (TP) (50%), and faecal coliforms (95.61%) was achieved in the C. papyrus cultivated wetland. Whereas up to 62.85% reduction of total suspended solids was observed in P. australis cultivated systems. These findings showed that CWs are effective systems for wastewater reuse or reclamation. Haddis et al. [21] employed the used of C. papyrus and S. validus for bioremediation of municipal sewage in a tropical weather under suboptimal conditions of flow to examine the potentials of HSSF-CWs. The outcomes of the study indicated that up to 81% removal of BOD5 in C. papyrus, 76% in S. validus and 48% in control; TSS removal was 76% in C. papyrus, 75% in S. validus and 54% in control; COD removal showed 65% in C. papyrus, 62% in S. validus and 32% in control was attained from the HSSF-CW systems. The authors concluded that CWs can work well under unpredictable water flow and can be a sustainable technology of choice for low-income countries, particularly in tropical regions.

Nonetheless, Lu et al. [22], studied and evaluated the performance of A. calamus, C. indica, and I. aquatica in bioremediation of swine wastewater and power generation through an integrated constructed wetland-microbial fuel cell (MFC) process. The results of the study entail that the absorption ability of the C. indica was found to be higher than those of A. calamus, and I. aquatica systems. While in bioelectricity generation, I. aquatica had the greatest effect with an average output voltage of 752 ± 26 mV. These findings demonstrated the likelihood of a concurrent treatment of wastewater and bioelectricity generation through synergy of constructed wetland and MFC systems. Furthermore, Haydar et al. [23] designed an innovative hybrid flow constructed wetlands (HCFWs) for bioremediation of municipal sewage water. The workability and performance of the engineered CWs was measured through treatment of municipal wastewater using P. stratiotes and Typha at 4 days detention time. The outcomes obtained designated that optimum removal of BOD, COD, TKN, TSS and TP observed for P. stratiotes that is cultivated in HCFWs was 84%, 80%, 71%, 82% and 88% respectively. In summary of all the research studies and findings alluded above, it can be categorically deduced that the discoveries have demonstrated the reliability and capabilities of CWs in phytoremediation of wastewater.

3. Overview of hydroponic systems in wastewater treatment

Hydroponic system can be defined as a technique of growing plants without the use of soil [24]. In the context of biological wastewater treatment, plants are cultivated using nutrient-rich wastewater in hydroponic wastewater treatment systems. This procedure is considered as an indispensable step in phytoremediation wastewater, in which plant roots are responsible for degradation of excess nutrients [25]. Therefore, the application of these systems encourages the adoption of natural ecosystem for wastewater management and bioremediation processes of wastewater [26]. Classification of hydroponic cultivation systems can be categorised based on nutrient feeding to the plant roots [27]. In addition, they can also be classified into two major groups; hydroponic systems that do not involve substrate such as the raft systems and the nutrient film technique (NFT) [28] and the cultivation systems that involves substrate, which ensures roots anchorage, and serves as medium for microorganisms’ attachment and water-nutritional flywheel [29]. Different types of free-floating macrophytes such as (A. pinnata, S. polyrhiza, P. stratiotes, E. crassipes, M. mutica, S. molesta, L. punctata, and R. fluitans) [30,31] have been cultivated in hydroponic systems in phytoremediation of wastewater. Besides, the ability of this cultivation system to act as eco-friendly technology for pollutant removal solely depends on factors like composition of wastewater, sunlight, growth of microorganisms and plant roots contributing directly and indirectly in the bioremediation processes of wastewater. Thereafter, the plant root system enhance the growth of the microorganisms by releasing metabolites, which serve as food for the microorganisms and, thus improving the rate of nitrification and denitrification process in biological wastewater treatment systems [29]. In furtherance to pollutant removal, the mainstreaming of wastewater and hydroponics system can support cultivation of crops and production of biomass. Hence, ensuring food safety and wealth creation for poor communities [32].
3.1. Advantages of hydroponic systems over constructed systems in wastewater treatment

In the hydroponic system, greenhouse environment or conditions is required to enhance adequate plant growth. The primary purpose of the greenhouse is to substitute natural resources such as carbon dioxide (CO$_2$) and sunlight essential to promote growth, and protect crops against adverse environmental conditions, particularly during winter season [29]. However, similarities exist between hydroponic wastewater treatment system and constructed wetlands, wherein the bioremediation processes of wastewater in hydroponic systems involves the combined effects of microorganisms, plants, nutrients, biological, chemical and physical processes [33]. Moreover, it has been established that hydroponic wastewater treatment plant is eco-friendlier and cost effective technology in comparison to the constructed wetlands. A significant and glaring feature of constructed wetland treatment systems over the hydroponic process is that CWs use plants with less economic value for bioremediation of wastewater [34]. On the other hand, hydroponic systems promotes the cultivation of useful crops and plants of high economic importance in wastewater remediation processes. Thus, hydroponic technologies of wastewater treatment are cheaper, and can be instituted onsite within small space area [35].

3.2. Applications of hydroponic systems in wastewater bioremediation

Wastewater treatment through cultivation of plants in lab-scale hydroponic bioreactors is one of the promising and sustainable bioremediation methods for municipal, agricultural and industrial wastewater. The large space requirement and dependence of constructed wetlands on precarious environmental factors have triggered the applications of hydroponic ponds for the cultivation of different species of plants to facilitate biological treatment of wastewater in a controlled environment. The applications of hydroponic systems in wastewater treatment have been reported in several studies. Baweic et al. [36] evaluated the effects of temperature and insolation on nitrate-nitrogen uptake by macrophytes using greenhouse hydroponic cultivation systems. Data obtained from daily sunshine and temperature for a period ranging from 2013-2016 via a meteorological station was used in the study. The information deduced from the study showed that at moderate weather conditions, the amount of solar radiation reaching the Earth’s surface is inadequate to ensure year-round activity. Also, the Authors further explained that no correlation was found between the measured parameters in the case of air temperature, which in essence indicates temperature lacks influence on macrophytes viability and efficiency to remove nitrate from the wastewater. Gebeyehu et al. [37] studied the phytoremediation of brewery wastewater using $T$. latifolia in a hydroponic bioreactor. The hydroponic system was adopted in the study to monitor water quality parameters comprising plant growth rate and degree of nutrient uptake at five days retention with varying surface loadings and mean hydraulic loading level of 0.023 m$^3$ m$^{-2}$ d$^{-1}$. The findings obtained from the study demonstrated that a significant reduction ($p < 0.05$) was observed in the treated brewery wastewater samples which varied between 54% and 80% for TKN, 42% and 65% for ammonia nitrogen, 47% - 58% for nitrate and 51% -70% for phosphate. Also, in the cultivation system, a biomass of 0.61 - 0.86kg dry weight m$^{-2}$ was generated. Ndulini et al. [14] studied the degree of faecal coliforms and nutrient uptake in wastewater by cultivation of macrophytes in hydroponic systems at 24, 72, 144, 192 and 240 hours retention time for 3 months. Spectrophotometric methods were used to measure and monitor reduction efficiency of ammonia, nitrite, nitrate and total phosphorous while membrane filtration technique was used for faecal coliform counts. The information from the results indicated that up to 87%, 96%, 99%, 87% and 92% reduction was recorded for ammonia, nitrite, nitrate, total phosphorous and faecal coliforms, respectively. The authors concluded that the applications of the system would provide potential approach to the challenges of wastewater treatment in areas where conventional methods are impractical or costly. Egbuikwem et al. [38] employed biological methods for wastewater treatment composed of textile, pharmaceutical, agricultural and organic discharges for cultivation of lettuce and beets using hydroponic systems. The outcomes of the study reveals positive signal for reuse of the wastewater samples for food production.

Furthermore, nitrogen being an element of ribonucleic acid (RNA), deoxyribonucleic acid (DNA), amino acids, and other biochemical constituents is as an essential element for all living creatures. However, plants consume nitrate as the main source of nitrogen hydroponic systems because the
concentration of nitrate in this system is greater than the concentrations of \( \text{NH}_4 \) and \( \text{NO}_2 \). Additionally, for the purpose of photosynthesis, dissolved minerals and water are passed through the xylem from the roots. The capillary force determines the transportation of minerals and water through translocation from the interconnecting organs and evaporation from plants leaves, leading to the suction of water and minerals. The stomata form small pores where oxygen and carbon dioxide usually diffuse between leaves and the atmosphere [39]. Also, in hydroponic system nutrients breakdown through biological nitrification, denitrification, and assimilation by plants roots in the form of nitrate (\( \text{NO}_3^- \)) and ammonium (\( \text{NH}_4^+ \)) [40]. Despite the mentioned numerous advantages supporting the application of hydroponic systems, the definite energy consumption involved in this technique is nearly 17% [41]. Indeed, to maintain the temperature requirement of hydroponic systems in a greenhouse during winter season, a supplementary heating system is necessary [26]. In summary, the aforementioned research study has demonstrated that the applications of hydroponic systems in wastewater is simple, inexpensive and environmentally friendly approach. However, the advantages of hydroponic systems in the treatment of wastewater using different plant species outweigh its disadvantages.

4. Conclusion
Finding a lasting solution to the menace of water pollution and management has become an enormous concern to the government, policymakers and the public. The applications of phytoremediation techniques in wastewater through the use of constructed wetlands and hydroponic systems have shown to be an effective and cheap method for simultaneous cultivation of useful plants and wastewater remediation. However, the mode of operation of constructed wetlands and hydroponic systems in wastewater are similar as they apply combined effects of biological, chemical and physical methods in both systems. Also, they are eco-friendly and sustainable methods. Nevertheless, hydroponic systems are cost effective, require small space and facilitates the production of valuable crops and plants of high economic importance during wastewater remediation processes. The main advantage of constructed wetlands is that it covers wide area of applications as it can be used in habitat formation, flood control and wastewater decontamination. Therefore, these methods are particularly useful for low-income countries, especially those in tropical areas. Wastewater remediated from the cultivation of plant species is suitable for agricultural purposes and can be discharged into fresh waterbodies. However, further studies can be employed through phytoremediation technique for wastewater reclamation and biomass production on industrial scale.

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