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REVIEW

Role of water hyacinth *(Eichhornia crassipes)* in integrated constructed wetlands: a review on its phytoremediation potential

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Abstract
Now a days a very active research area is to develop highly efficient and environmental friendly treatment technologies for wastewaters. A very reliable treatment technology is for treating different types of wastewater is integrated constructed wetlands. Phytoremediation is primary treatment process of constructed wetlands. It is actually cleaning of environment through vegetation. A plant water hyacinth is one of the very proficient plant utilized in constructed wetlands. To review role of water hyacinth in integrated constructed wetlands, its uptake mechanism in terms of heavy metals, organic matter, nitrogen and phosphorus has been studied and demonstrated in this paper. Possibility of using water hyacinth for the removal of contaminants existing in various types of wastewaters is the focal objective of this paper, has been studied and demonstrated in the form of removal efficiency. Now a days the focus is on sustainable approach for developing wastewater treatment capabilities. Utilization of invasive plants for phyto-technologies for the abatement of pollution, can indeed support the sustainable management for treating wastewater.

Keywords Integrated constructed wetlands · Pollutant removal · Phytoremediation · Wastewater treatment technology · Water hyacinth

Introduction

Water hyacinth is aquatic plant with scientific name *Eichhornia crassipes* and an invasive species. It has been originated from Amazon Basin, South America. It has been spread among tropics and sub-tropics since 1800s. It reproduces sexually by forming seeds through flowers and budding while it can reproduce asexually as well. Water rich with nutrients with temperature range of 28 °C to 30 °C, 20 mg/L Nitrogen, 3 mg/L Phosphorus, salinity < 2%, pH 6.5 to 8.5, and 53 mg/L potassium are the best promising conditions. Water hyacinth has been used as an ornamental crop for many centuries and belongs to the family of Pontederiaceae (Tellez et al. 2008). It can hinder the sunlight to penetrate inside, when it grows on the surface of water because of its heavy spread (Tiwari et al. 2007).

Roots are comparatively longer that can suspend in the water. This kind of root structure can provide proper conditions for the proper functioning of "aerobic microorganisms". These microorganisms can covert nutrients and organic matter into those compounds that can be readily consumed by plant. (Klumpp et al. 2002).

Water hyacinth *(Eichhornia crassipes)* has been reported worldwide as one of the highly productive plant. Its growth is very rapid in non-indigenous countries because of the absence of competitors and natural enemies (Malik 2007). Uncontrollable growth of this plant may also be problematic especially for irrigation systems, it can rapidly grow on water bodies (Kunatsa et al. 2013). Its growth is 60 kg per m^2 of surface of water through so it can be reason of serious impacts on sustainable development of economy (Ganguly et al. 2012).

There are many biological, chemical and physical methods that are employed for the purpose of wastewater treatment before the final disposal of it. Biological methods are more remarkable as reported formerly as well and phytoremediation is one of them (Roongtanakiat et al. 2007).

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Foremost conception of phytoremediation is plant–microbe interactions for the removal of pollutants and amongst phytoremediation technique "artificial wetlands" are the most common and effective technology for the wastewater treatment. These artificial wetlands can also encourage biodiversity, it aids to improve the quality of air and prevents climate change through reduced formation of carbon dioxide, biomethylation and hydrological functions. Artificial wetlands stand very environmental friendly economic, simple, applicable and ecologically sound technology, and also it requires comparatively lesser land space (Azaizeh et al. 2003; Lu 2009).

Constructed wetland (CW) is an artificial wetland it is a biogeochemical and highly effectual system for the wastewater treatment from different sources such as industrial, domestic, mining, pharmaceutical sectors. It must be distinguished that choice of appropriate plant is vital for the application of phytoremediation (De Stefani et al. 2011).

Plant should have high capabilities of pollutant uptake, and faster growth rate in wastewater. These abilities vary from plant to plant, and species to species (Roongtanakiat et al. 2007).There are many plants that can be utilize for this purpose *Eichhornia crassipes* is one of them, There are several other species of plants for example; *Typha latifolia, Water lettuce, and Penny wort*. that have also demonstrated considerable percentage removal (Vymazal and Kröpfelová 2008; Lu et al. 2010; Dipu et al. 2011; Girija et al. 2011; Loan et al. 2014; Ali et al. 2020; Kumar and Deswal 2020).

Water hyacinth *(Eichhornia Crassipes)* is very common in Pakistan too. Especially in Gujranwala district of Punjab province it is easily inhabiting marshy areas and rapidly multiplying (Qaisar et al. 2005).

Methodology

It is an observational study directed by analyzing research articles. Application in the form of pollutants removal efficiency in integrated constructed wetlands and uptake mechanism of water hyacinth plant along with its general phytoremediation process has been evaluated in this review.

Constructed wetlands using water hyacinth *(Eichhornia crassipes)* for wastewater treatment

As discussed, earlier water hyacinth *(Eichhornia crassipes)* is particularly wildest growing photosynthetic plant, 10 plants could produce 600,000 more with in growing season of 8 months that can easily covers 0.4 ha of water surface (Castro and Agblevor 2020). Table 1 demonstrate the growth factors and range of this plant.

Table 1 Growth conditions of *Eichhornia crassipes* (Hammad 2011)

Factors	Range
Growth rate (plant number)	By 10 plants in 10 months, 1610 plants can produce
Growth rate (on surface)	1.012 to 1.077 m^2/day
pH of water	6–8
Temperature of water	10–40 °C
Salinity of water	< 5 mg/L

Growth on surface of water can create different environment than the exposed water. Its leaves create dense canopy that causes shades and prevents the growth of algae and thus controlling the oxygen production, hence this can maintain pH at approximately neutral levels. Moderation in water temperature fluctuations and wind induced turbulence that causes mixing also reduced because of the mass of this plant. This causes low oxygen levels inside the water and benthic zone is completely anaerobic. Root system of this plant is very extensive that can provide sufficient surface area to microorganisms for attachment (Ajayi and Ogunbayio 2012).

Requirements for systems of secondary treatments are, hydraulic loading rate < 8 cm d^{-1}, water depth should be < 0.9 m, organic loading rate < 100 kg BOD_5 ha^{-1}, and retention time > 6 days. Aspect ratio of cells (length: width) have to be > 3:1 to ensure plug flow condition as much as possible (Moyo et al. 2013).

Several cells are recommended to construct, and aeration is also possible to manage the concentration of oxygen, but it can make operation of the system quiet expensive. Harvesting must be made frequently for the better growth of plant. Approximately 12 to 22 kg m^{-2} of wet weight densities of plant are recommended for best possible treatment with roughly or loosely packed plants with 80 to100% coverage of surface (Valipour et al. 2015).

For the better accomplishment of harvesting procedure, it stands essential to construct water hyacinth ponds, with intensive harvesting. This has inclination or tendency enhancing the overall cost of hyacinth system and maybe it also develops issues for the disposal of surplus material. Vegetation management degree is depending upon goals of water quality of that project and choice between regular sludge removals or harvesting of plants (Castro and Agblevor 2020). Before disposing off the harvested material it is mandatory to add a step of drying up because water hyacinth is composed of 95% water. After that landfill can be used for its disposal or somewhere else as allowed by the regulatory authority. If there is higher concentration of metals in the wastewater it is reasonable to check the metal content in the dried plants and these levels must not be exceeded the allowed permissible limit for utilization or disposal. Methane production from sludge and anaerobic digestion, and utilization of plants as a feed for animals are technically viable or feasible process (Mokhtar et al. 2011).

Mechanism for heavy metals removal by water hyacinth (*Eichhornia crassipes*)

Water hyacinth is having high absorbing rate of contaminants can tolerate exceptionally polluted environment it also has enormous rate of biomass production that is the reason it can easily remediate heavy metals like zinc, nickel, arsenic, mercury, lead and copper (Ali et al. 2020).

There are basically three mechanisms from which the removal of contaminants occurs named root absorption, foliar absorption, and adsorption (Zhang et al. 2015).

Root absorption: In the root absorption water and contaminants get absorbed in roots of plant. Carboxyl groups are present in the roots systems causes cation exchange inside the cell membrane and this can be procedure of moving the heavy metals in the roots where the process of active absorption occur (Khan 2009). Foliar absorption: foliar absorption occurs when contaminants are passively absorbed by stoma cells and cracks in cuticle, comparatively low amount of contaminant absorption takes place by foliar absorptions. Adsorption: water hyacinth has feathery and dense fibrous roots that help them to trap suspended solids and bacteria. They offer proper attachment sites for the growth of fungus and bacteria; hence the contaminants get absorbed easily also because of ionic imbalance throughout the cell membrane (PN and Madhu 2011).

Mechanism for organic matter removal by water hyacinth *(Eichhornia crassipes*)

Particulate matter gets settle in the bottom of the pond while suspended solids get entrapped by the roots accumulate and metabolized by microbes and also settled by gravity.

The mechanism for the removal of dissolved organic matter (DOM) is mainly processed by bacteria, existing on biofilms, through bio-oxidation (Ajayi and Ogunbayio 2012).

Dissolved organic matter removal mechanism also comprise uptake by plant in addition to degradation or accumulation in sediments after sorption. The bacteria use organic matter as a food for energy production and new cells' production or synthesis. Energy production process involve biochemical reactions and these reactions needs electron-acceptors for the oxidation of organic matter and if they are using free oxygen for that purpose than they become very dominant because of their energy efficiency (Wang et al. 2012). Here a summarized reaction of the biochemical stages occurring there is mentioned below.

$$C_5H_7O_2N + O_2 \rightarrow 5CO_2 + NH_3 + 2H_2O + \text{energy}$$

$C_5H_7O_2N$ is bacterial biomass in the form of generalized formula. If free oxygen is absent, then bacteria utilize sulphate and nitrate as electron-acceptors. Water column can be distributed into three zones depending upon the status of oxygen of water under the floating plant. Zone 1 is the area of rhizosphere and aerobic respiration occur there (Loan et al. 2014). Concentration of oxygen is decreases in the water column along with depth and reached to almost zero near Zone II. In Zone II the facultative anaerobic respiration is primarily the microbial metabolism of the suspended biomass, where microorganisms use nitrate ferric iron, and manganese as a source of electron acceptor. If these electron acceptors are absent than true anaerobic microorganisms use carbon dioxide and sulphate as electron acceptors. These situations happen in the detritus layer plus in the sediments lie beneath in Zone III (Shah et al. 2010).

Mechanism for nitrogen removal by water hyacinth *(Eichhornia crassipes)*

Removal of nitrogen is dependent upon cultural density, growth rate of plant and different environmental parameters for example temperature and solar radiation. Hyacinth plants can assimilate nitrate and ammonia simultaneously while other plants prefer ammonia over nitrate (Anandha and Kalpana 2015). Transformation of nitrogen include some basic procedures: nitrification (from ammonium to nitrate), immobilization (from ammonium and nitrate to organic nitrogen), mineralization (from organic nitrogen to ammonium) and volatilization and denitrification (from nitrate to nitrous oxide and nitrogen gas) (Kumari and Tripathi 2014).

Mechanism for phosphorus removal by water hyacinth *(Eichhornia crassipes)*

Removal of phosphorus occur by uptake of plant, precipitation in the water column, and retention by the underlying sediments. Phosphorus is generally retained, its ultimate or final removal is attained by removing the sediments and harvesting the plant (Sooknah 2000).

3 Results and discussions

As it has been discussed earlier that main process that is going on inside the integrated constructed wetlands is phytoremediation, there are two tables listed below that demonstrate water hyacinths' removal efficiency in terms of phytoremediation. Table 2 shows removal efficiency in terms of organic and in organic pollutants while Table 3 shows the removal efficiency in terms of heavy metals.

Table 2 Studies on removal of organic and inorganic compounds by means of water hyacinth through phytoremediation

Wastewater type	Organic and inorganic compounds	Result highlights	References
Sewage drain	BOD COD Sulfates Phosphate TDS	Water hyacinth Reduce: BOD:1442.7 COD:1967.3 Sulfates: 1148.2 Phosphate:7225.4 TDS: 911.5 g m^{-2} d^{-1}	Mahfooz et al. 2021
Rice mill wastewater	TP COD	Water hyacinth Reduce: TP: 77.2% COD:71.87%	Kumar and Deswal 2020
Kitchen wastewater	TDS PO_4–P NH_3–N NO_3–N K^+	Concentration reduced to: TDS: 63.71% PO_4–P: 98.05% NH_4–N: 94.36% NO_3–N: 99.01% K^+: 83.30%	Parwin, and Karar 2019
Wastewater	Formaldehyde	At 20ºC, 92.7% removal occur in 10 days and it reaches to 100% with 30ºC	Gong et al. 2018
Nitrogen-polluted wastewater	Total nitrogen	TN removal efficiency in the wetland containing water hyacinth was 63.9%	Mayo and Hanai 2017
Wastewater (Domestic)	COD TOC $PO^4{}_3$ NH_3	Removal rate was found between 12 to 15 days while the optimum rate of growth was occurred in 18 days. It removed: 95% of COD 85% NH_3 45% $PO^4{}_3$ 45% TOC	Rezania et al. 2016
Wastewater (Domestic)	BOD COD Total phosphorus Total suspended solids Total nitrogen PO_4–P NH_3-N	Water hyacinth Reduce: COD: 79%, TN: 76.16%, BOD removed to 86%, TP: 44.84, TSS: 73.02, NH_3–N: 72.48%, PO_4–P: 38.69%, 14 h was HRT	Valipour et al. 2015
Sewage water	Phosphate Nitrate Ammonia	Papaya and Water hyacinth incorporated in system removed 67% ammonia 71% phosphate and 74%nitrate	Anandha Varun and Kalpana 2015
Wastewater (Domestic)	$PO_4{}^{3-}$ $NH^+{}_4$ Total Suspended Solids COD	Water hyacinth and water glory comparison results in removal of 44.4% to 53.4 COD, 37.8% to 53.3 for TSS 57% to 61% for $PO_4{}^{3-}$ 27% to 33% for $NH^+{}_4$, High values (Water hyacinth) Lower values (Morning glory)	Loan et al. 2014
Wastewater (Municipal)	PO_4–P NO_3-N COD BOD TKN	They used mixed culture of water hyacinth and *Salvinia natans* that removed, 57% PO_4–P 27% NO_3–N 83.2% COD 84% BOD 53%TKN	Kumari and Tripathi 2014

Table 2 (continued)

Wastewater type	Organic and inorganic compounds	Result highlights	References
Wastewater (Domestic)	Total phosphorus Total nitrogen COD	Removed: 75% of TP and TN while 80% COD. There is also 40% biomass increase has been seen subsequently in 14 days	Rezania et al. 2013

Removal efficiency of water hyacinth in terms of organic and inorganic compounds

Water hyacinth has been widely studied for removing organic matter and for the removal of inorganic compounds. Table 2 shows different studies and their results highlights along with organic and inorganic compounds removed from different wastewater, result highlights depicts the exact value of removal in terms of percentages.

efficiency of water hyacinth in terms of heavy metals

Table 3 shows different studies and their results highlights along with heavy metals removed from different wastewater; result highlights depict the exact value of removal in terms of percentages.

Statistical analysis of water hyacinth based constructed wetlands

Figures 1 and 2 demonstrate the performance of integrated constructed wetlands incorporated with water hyacinth this data is based on complied results of fourteen systems in USA and Japan. Loading for BOD_5 and TSS given in units of kg ha^{-1} d^{-1} and for TN and TP given in gm^{-1} yr^{-1}. Efficiency has been shown in form of percentage (Vymazal and Kröpfelová 2008).

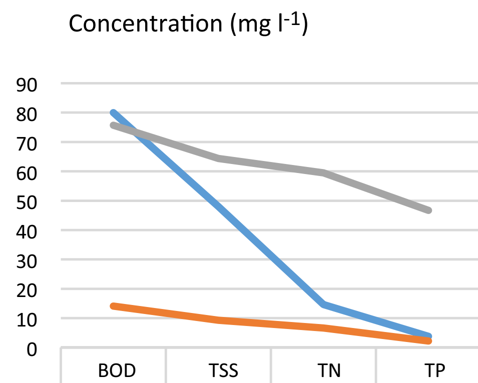
Conclusion

It is concluded that *Eichhornia crassipes* is potential plant in constructed wetlands. Removal efficiency of this plant for heavy metal and organic matter, from wastewater of various origin and nature is explained in this paper and it has been found that this plant is suitable for treating highly polluted industrial and domestic wastewater. Uptake mechanism in terms of heavy metal, organic matter, nitrogen and phosphorus has also been demonstrated in this paper that will positively help for finding new innovative phyto-technologies as well as large scale utilization of using water hyacinth in future.

In future, research and development possibly may focus on utilization of water hyacinth in largescale application along with its cost benefit analysis in integrated constructed wetlands. It is also inexpensive unlike advance technologies that prerequisites more cost for the treatment of wastewater that is why it is proposed that utilization of this plant is highly sustainable approach for wastewater treatment. Furthermore, it has been suggested that similar phyto-technologies that support sustainable management for treating wastewater should be studied in detail.

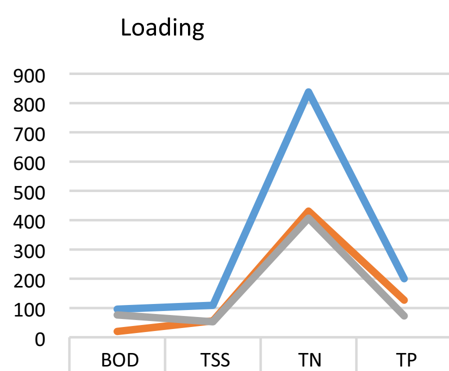
Table 3 Studies on removal of heavy metals by means of water hyacinth through phytoremediation

Wastewater type	Organic and inorganic compounds	Result highlights	References
Sewage drain	Chromium Lead Nickel Copper	Water hyacinth assisted with two bacillus species removed 72.4% chromium, 83.3% lead, 82.35% nickel, and 63.63% copper	Mahfooz et al. 2021
Wastewater	Cadmium Arsenic Mercury	Dry weight of water hyacinth accumulating heavy metals were highest in cadmium and smallest for mercury that is 166.25 ppm and 0.032 ppm, respectively	Nazir et al 2020
Irrigation canals	Cadmium, Cobalt, Chromium, Copper, Nickle, Lead, Zinc, Manganese, Iron	Concentrations of these heavy metals were higher in roots. Bioaccumulation factor was > 1.0 and translocation factor was < 1.0 for all heavy metals	Eid et al. 2019
Industrial mines wastewater	Hexavalent Chromium	99.5% of Cr(VI) removal in first 15 days occur	Saha et al. 2017
Artificial wastewater was prepared and $NiCl_2$-$6H_2O$ was added to get concentration of 1,2,3and 4 mg per liter	Nickel	Very rapid adsorption for the duration of first 24 h. Accumulation was higher in roots	Gonzalez et al. 2015
Deionized water with $Cd(NO_3)_2.4H_2O$ (artificial wastewater)	Cadmium	They used pyrolyzed biochar as of *E. crassipes.* Causes 100% removal in an aqueous medium at initial Cd 50 mg/L within 1 h	Zhang et al. 2015
Hydroponic medium	Mercury	Mercury was accumulated in ionic form in roots, leaves and petiole tissues with dry weight of 1.99, 1.74 and 1.39 mg/g	Malar et al. 2015
Diluted Stock solution in drinking water	Arsenic	20 g of *E. crassipes,* based prototype filter was eliminating 80 to 84% of arsenic with concentration of 250 and 1000 mg/L	Brima and Haris 2014
Industrial wastewater	Zinc, Copper, Cadmium, Chromium	Highest amount of removal was recorded on 10^{th} day of experiment, roots were highly accumulated while leaves were least accumulators	Yapoga et al. 2013
Composting wastewater	Zinc, Cadmium, iron, Chromium, Copper, Manganese, Nickle, Lead	Overall metal concentration rises through composting and aby composting also metal concentration was detected in TCLP	Singh and Kalamdhad 2013
Artificial lake water	Zinc, Copper, Lead, Cadmium	Pb > Cu > Cd > Zn as the order of decreasing concentration their initial concentrations was; Zn500g/L, Cu 250 g/L, Pb 250 g/L, and Cd 50 g/L. The removal efficiency after 8 days: 11% and 26% Pb 8% and 24% Cu 18% and 57%Zn 24% and 50% Cd At pH 8 and pH 6	Smolyakov 2012



	BOD	TSS	TN	TP
IN	80	48	14.6	3.8
OUT	14.1	9.3	6.6	2.2
Efficiency	75.7	64.4	59.5	46.7

Fig. 1 Treatment effect (concentration)



	BOD	TSS	TN	TP
IN	96	109	838	200
OUT	20	56	431	127
Remediation	76	53	407	73

Fig. 2 Treatment effect (loading)

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