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Water hyacinth (*Eichhornia crassipes*) – An efficient and economic adsorbent for textile effluent treatment – A review

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Abstract Phytoremediation through aquatic macrophytes treatment system (AMATS) for the removal of pollutants and contaminants from various natural sources is a well established environmental protection technique. Water hyacinth (*Eichhornia crassipes*), a worst invasive aquatic weed has been utilised for various research activities over the last few decades. The biosorption capacity of the water hyacinth in minimising various contaminants present in the industrial wastewater is well studied. The present review quotes the literatures related to the biosorption capacity of the water hyacinth in reducing the concentration of dyestuffs, heavy metals and minimising certain other physiochemical parameters like TSS (total suspended solids), TDS (total dissolved solids), COD (chemical oxygen demand) and BOD (biological oxygen demand) in textile wastewater. Sorption kinetics through various models, factors influencing the biosorption capacity, and role of physical and chemical modifications in the water hyacinth are also discussed.

1. Introduction

The discharge of toxic effluents from various industries adversely affects water resources, soil fertility, aquatic organisms and ecosystem integrity. Appearance of colour in discharges from various industries is one of the major problems encountered in the textile industry. It is difficult to predict the characteristics of textile wastewater by reported values in the literature as every industry is unique in respect to the production, technology and chemicals used. The textile waste water is rated as the most polluting among all in the industrial sectors (Vilaseca et al., 2010; Awomeso et al., 2010). The textile industry consumes large quantities of water and produces large volumes of wastewater through various steps in dyeing and finishing processes. The textile waste water is a complex and variable mixture of polluting substances like inorganic, organic, elemental and polymeric products (Brown and Laboureur, 1983). Among complex industrial wastewater with various types of colouring agents, dye wastes are predominant. The textile wastewater containing dye substances is not only toxic to the biological world, its dark colour blocks sunlight that leads to severe problems to the ecosystem. (Choi et al., 2004).

Due to low biodegradation of dyes, convectional biological treatment process is not very effective in treating dye wastes.

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The usual treatment processes like physical and chemical methods such as coagulation, flocculation, adsorption, membrane filtration and irradiation. (Robinson et al., 2001) achieve good decolorising efficiency but they have two main constraints: high cost and the production of the significant amount of sludge material that requires final disposal again. Among all the methods adsorption is one of the most effective methods of removing dyes from waste sewage (Deans and Dixon, 1992; Nigam et al., 2000). The process of adsorption has an advantage over the other methods due to its sludge free operation and complete removal of dyes even from dilute solutions. Activated carbons have been extensively utilised in various industrial adsorption and separation processes because of its efficient adsorption of the organic compound. However there are a number of drawbacks in utilisation for decolourisation like higher cost and operational losses such as combustion at high temperature, pore blocking and hygroscopicity. Recently, a considerable amount of research has been undertaken to find cheaper substitutions to activated carbon. Recent developments of new strategies of making use of low cost, easily available biological and agricultural waste materials for the adsorption process is gaining much importance to replace activated carbon. Some of the low cost adsorbents that are tested for the dye sorption process are rice husk (Manoj kumar, 2013), bark, hair and coal (Ho and McKay, 1999), wood dust (Garg et al., 2004), tree bark powder (Paul Egwuonwu, 2013), peat (Fernandes et al., 2006), lignin (Cotoruelo et al., 2010), wheat bran (Ata et al., 2012; Ozer and Dursun, 2007), brown sea weed (Vijayaraghavan and Yun, 2008), banana and orange peel (Annadurai et al., 2002), fly ash (Janos et al., 2003), pineapple stem waste (Hameed et al., 2009), water hyacinth pulp powder, tuberous pulp, sugarcane pulp, and coconut pulp (Pramanik et al., 2011).

Aquatic macrophytes treatment system (AMATS) is a well established environment protective technique as a phytoremediation procedure for removing pollutants. Some freshwater macrophytes including *Potamogeton lucens*, *Salvinia hergozi*, *Eichhornia crassipes*, *Myriophyllum spicatum*, *Cabomba* sp., and *Cratophyllum demersum* have been investigated for their potential in heavy-metal and colour removal. Their mechanisms of metal and colour removal by biosorption can be classified as extracellular accumulation/precipitation, cell surface sorption/precipitation, and intracellular accumulation (Rai et al., 2002). Among these above mentioned aquatic plants *E. crassipes* (E.C.) (Water hyacinth) that belongs to the family pontederiaceae stands as a challenging, most productive invasive aquatic plant on earth showing extreme risk to the ecosystem. Water hyacinth originated in the American tropics and spread to all tropical climate countries. In India, they can be found in large water areas in the Kerala backwaters, ponds and lakes. Due to vegetative reproduction and vigorous growth rate of this plant, it dramatically impacts water flow, blocks sunlight from reaching native aquatic plants, and starves the water of oxygen, often killing fish and also acts as a prime habitat for mosquitoes. A typical biomass from land plants is composed of 30–50% cellulose, 20–40% hemicellulose and 15–30% lignin. It is also found to have high nitrogen content and in combination with cow dung it can be used for biogas production (Bhattacharya and Pawan, 2010). Its enormous biomass production rate, its high tolerance to pollution, and its heavy metal and nutrient absorption capacities (Chanakya et al., 1993; Singhal and Rai, 2003; Ingole and Bhole, 2003; Liao and Chang, 2004; Jayaweera and Kasturiarachchi, 2004) qualify it for use in wastewater treatment ponds.

Considering the applications and utilisation of the water hyacinth in various above mentioned concepts, its major role in textile effluent treatment is recently undergoing higher attention to find an alternative for the currently available textile effluent treatment techniques. Thus the present review deals with the biosorption capacity of the water hyacinth for the treatment of textile dyes, textile waste water as well as heavy metals in textile industrial effluent.

2. Textile dye treatment

Textile industries utilize substantial volumes of water and chemicals ranging from inorganic compounds, polymers and organic products for wet-processing of textiles (Dos Santos et al., 2007). There are more than 8000 chemical products associated with the dyeing process listed in the colour index, including several types of dyes like acidic, reactive, basic, disperse, azo, diazo, anthraquinone and metal-complex dyes (Banat et al., 1996). The removal of colour from dye bearing effluents is one of the major problems as they contribute to the major fraction of biobiological oxygen demand (BOD). Among the new emerging treatment methods of dye removal by aquatic macrophytes, various reports on the removal of different types of dyes by the aquatic weed water hyacinth have gained attention in recent days.

The cationic dye methylene blue was widely studied for its removal from aqueous solution by the water hyacinth. Low et al. (1995) on laboratory investigations studied the potential of biomass of non-living, dried, roots of the water hyacinth (*E. crassipes*) to remove two basic dyes, methylene blue and Victoria blue from aqueous solutions. Various parameters studied included pH, sorbent dosage, contact time and initial concentrations and the sorption data represented by the Langmuir isotherm. Further the maximum sorption capacity of 128.9 and 145.4 mg/g respectively for methylene blue and Victoria blue was found out. Thus the author concluded the water hyacinth root as a cheap source of biosorbent for basic dyes. The detailed kinetics and mechanism of adsorption of methylene blue from aqueous solution by nitric-acid treated water-hyacinth was studied by El-Khaiary (2007). The author found that the adsorption rate was fast and more than half of the adsorbed-MB was removed in the first 15 min at room temperature, which makes the process practical for industrial application. The overall rate of dye uptake was found to be controlled by external mass transfer at the beginning of adsorption, and then gradually changed to intraparticle diffusion control at a later stage. It was concluded that the adsorption kinetics at room temperature could be expressed by the pseudo second order model, while at higher temperatures (45–80 °C) and low dye concentration (97 mg/L) both Lagergren's model and the pseudo second order model were used to predict the kinetics of adsorption. In a recent publication, Kanawade and Gaikwad (2011) studied the adsorption property of the water hyacinth and activated carbon in removing methylene blue from aqueous solution. Kinetics and isotherm studies were carried out for both the adsorbents in which the water hyacinth fitted more accurately to the Langmuir model. Saltabaş et al. (2012) studied the biosorption capacity of water hyacinth roots on the cationic dyes methylene blue and malachite green. The biosorption capacity was found to be increased with a rise in temperature. The equilibrium fitted well with the Langmuir model and the biosorption capacity value for malachite green was 42.55 mg/g and methylene blue was 44.64 mg/g at 313 K. In an another study, Soni et al., 2012 found the water hyacinth root to be an efficient adsorbent for removing methylene blue from aqueous solution as it had shown 95% dye removal efficiency in an optimum experimental condition. Further the author concluded that WHRP as low cost adsorbent may be appropriate for designing batch or stirred tank flow reactors that can be used in small dyeing industries for direct solutions. Bioadsorption of various industrial dyes like methylene blue, Congo red, crystal violet, and malachite green from aqueous solution has been performed in the water hyacinth using lab-scale batch bioreactor (Nath et al., 2013) where maximum percentages of removal of the dyes were found to be 90%, 88%, 92%, and 90% for methylene blue, congo red, crystal violet, and malachite green, respectively. The adsorption kinetic suited with the pseudo second order and Langmuir isotherm described the equilibrium dye uptake.

Other varieties of dyes were also studied for its removal by water hyacinth. Tarawou et al. (2007) determined the surface characteristics and adsorbent properties of the water hyacinth biomass through the batch adsorption technique in the removal of methyl red. The authors concluded that the dye elimination was associated with strong electrostatic forces. El Zawahry and Kamel (2004) assessed the ability of *E. Crassipes* and its aminated derivative to adsorb six dyes that included reactive and acid azo and anthraquinone dyes from their solutions. The authors observed that rather than the raw E.C., the aminated derivatives with higher nitrogen and amino content have shown more attraction towards the anionic groups of the dye with higher dye adsorption rates. Removal or minimisation of reactive and acid azo and anthraquinone dyes from their solutions by 12% aminated raw E.C. with sandene shows a good adsorption capacity. Its strength values pKb increases with the increasing of the efficiency and capacity of the anion exchanger. Equilibrium data fit well with the Freundlich model of adsorption for six reactive and acid azo and anthraquinone dyes.

Binti Awang (2010) studied the potential of water hyacinth as adsorbent, in removing malachite green from aqueous solution and also identified the optimum conditions for the parameters involved. At the arrived optimum condition, the removal of malachite green was increased with the increase in initial concentration. In another study, stem water hyacinth (SWH) was used as an adsorbent for the removal of acid green 20 (AG20) as an anionic dye from aqueous solution. The equilibrium fitted well with the Langmuir II equation. (Aboul-Fetouh et al., 2010). Further, adsorption of an anionic dye Congo red by activated water hyacinth roots was studied by Rajamohan (2009). An effective pH of 6 was optimised for the adsorption of Congo red through batch studies. Redlich–Peterson isotherm best-fits with the Congo red adsorption isotherm data on all initial dye concentrations. Freundlich isotherm also showed comparable fit.

Vasanthy et al., 2011 removed the textile dyes red RB and Black B from their aqueous solutions by water hyacinth plant material. The efficiency of *E. crassipes* to remove the colour and degrade the dye was about 95% with Red RB and 99.5% with black B. The authors observed the changes in phytochemical components by GC–MS analysis before and after adsorption, where increased content of hexadecanoic acid and reduced phytol content were reported. Further it was also studied to establish the *Eicchornia* plants for vermicomposting with cow dung and leaves (See Table 1).

Table 1 Characteristic range of various parameters and heavy metals in textile wastewater.

S. No.	Parameters	Typical range	NEQS limit
1	pH	5.5–10.5	6–9
2	COD (mg/L)	350–700	Upto 150
3	BOD (mg/L)	150–350	Upto 80
4	TDS (mg/L)	1500–2200	Upto 3500
5	TSS (mg/L)	200–1100	Upto 200
6	Sulphides (mg/L)	5–20	1.0
7	Chlorides (mg/L)	200–500	1000
8	Chromium (mg/L)	2–5	1.0
9	Zinc (mg/L)	3–6	5.0
10	Copper (mg/L)	2–6	1.0
11	Sulphates (mg/L)	500–700	600
12	Sodium (mg/L)	400–600	–
13	Potassium (mg/L)	30–50	–
14	Cadmium (mg/L)	0.07–2	0.1
15	Iron (mg/L)	0.03–2.0	2.0
16	Nickel (mg/L)	0.5–3	1.5

The optimised condition for dye absorption and the kinetic models proposed for various forms of water hyacinth with dye substances is listed out in the Table 2. From the table it is clear that most of the dye absorption process by water hyacinth follows Langmuir isotherm kinetic model with an adsorption range of 8–200 mg/g. The variation of adsorption with pH can be explained by changes in surface property of the adsorbent and the dissociation constant of the dye. At lower acidic pH anions are easily adsorbed, while the cationic dye shows low adsorption since H^+ ions are in abundance in lower pH. Cationic dye and H^+ ions compete with the adsorption site and accounts for the decrease in adsorption activity of cations. At higher pH cations show good adsorption. At higher pH OH^- ions are in plenty and it can compete with the anionic dye, which accounts for low adsorption of anionic dye in higher pH. Thus anionic dyes are highly adsorbed at acidic pH and cationic dyes are highly adsorbed at basic pH (Aboul-Fetouh et al., 2010). Adsorbent dosage also varies significantly as the percentage of dye uptake increases with an increase in adsorbent quantity, but the capacity for adsorption decreases which may be due to two factors. First during adsorption, the adsorption sites are unsaturated and second can be due to interactions like aggregations, which result in decrease of overall surface area.

The percentage dye adsorption efficiency of different forms of water hyacinth vs. different dyes is given in Fig. 1. From Fig. 1 it can be observed that the different forms of the water hyacinth did not influence the percentage adsorption in a significant way. All the forms of water hyacinth seem to be more or less equal in efficiency in removing the dyes and most of the studies were carried out only with cationic dyes like methylene blue, malachite green, crystal violet etc. and very few studies were done with anionic dyes. Further studies on anionic dyes would give a clear picture in deciding the biosorption efficiency of water hyacinth.

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Table 2 Optimised conditions and kinetic models of various dye adsorption process through different forms of the water hyacinth.

WH state	Optimised condition	Model	Dye	Absorption amount	References
WH root	0.1 g of biosorbent in 50 ml solution at 200 rpm on a gyratory shaker for 2 h	Langmuir isotherm	Methylene blue Victoria blue	128.9 mg/g 145.4 mg/g	Low et al. (1995)
WH biomass	pH-8.0 30 °C 8.85×10^{-2} mol g^{-1}	Langmuir-type isotherm Tarawou et al. (2007)	Methyl Red		
WH root	pH: 6; initial dye concentration: 100 mg/L. Temperature:30 °C Adsorbent dosage: 0.1 g/50 ml	Redlich Peterson isotherm equations. Freundlich isotherm	Congo red	1 g/L	Rajamohan (2009)
WH stem	20 mg/L initial dye concentration, 1.0 g/L WH stem dose, and 9.0 h contact time at room temperature, pH 3	Langmuir isotherm	Acid green 20	200 mg/g	Aboul-Fetouh et al. (2010)
WH root Aq. soln	pH 9.5; 100 mg of biosorbent per 100 mL, initial dye concentration: 3 mg L^{-1}, contact time: 60 min, temperature: 20 °C, shaking rate: 150 rpm	Langmuir-type isotherm	Malachite green methylene blue	44.64 mg/g 42.55 mg/g	Saltabas et al. (2012)
WH root	pH 8; Initial dye concentration: 20 mg/L at room temperature. Adsorbent dosage: 10 mg/L	Langmuir and Freundlich isotherms	Methylene blue	8.04 mg/g	Soni et al. (2012)
WH dried leaves	pH 2, 50 °C, and 150 rpm 0.2 g of biomass and 50 ml of dye solution at 50 mg/L	Langmuir isotherm	BF-4B reactive red dye	20.38 mg/g	Módenes et al. (2013)
Alginate fixed WH	Initial dye concentration = 50 mg/L, pH 8, agitated at 150 rpm at room temperature for 200 min, 0.5 g of 6% biomass	Pseudo second order	Methylene blue, crystal violet	86.2 mg/g	Courtie and Mawere (2013)
HCl treated WH root	0.25×10^{-3} kg of adsorbent, initial concentrations of dye 0.05–0.250 kg/m^3, Temperature- 27 ± 2 °C, pH 6.9	Langmuir isotherm	Methylene blue	0.26 kg/kg	Uddin et al. (2013)
HCl treated WH root	pH = 1.5, adsorbent dosage = 1.25 g/L, equilibrium time = 3 h	Langmuir isotherm	Acid red 114	112.34 mg/g	Rajamohan et al. (2013)
Surface modified WH by SDS	pH 12; Dye solution:50 mL (1000 mg/L) adsorbent: 50 mg, agitated at 150 rpm	Langmuir analysis	crystal violet	116.3 mg/g	Kaur et al. (2013)
Aq. soln of WH	pH 7; Adsorbent dose:6.5 g/L, initial dye concentration: 65 mg L^{-1}, optimum contact time: 5 days, Temperature = 32 °C ± 2	Pseudo second order	Methylene blue	6.5 g/L	Nath et al. (2013)
	pH 6; Adsorbent dose:7.5 g/L, initial dye concentration: 75 mg L^{-1}, optimum contact time: 5 days, Temperature = 32 °C ± 2		Congo red	7.5 g/L	
	pH 8; Adsorbent dose:6.0 g/L, initial dye concentration: 70 mg L^{-1}, Optimum contact time: 5 days, Temperature = 32 °C ± 2		Crystal violet	6.0 g/L	
	pH 8; Adsorbent dose:7.0 g/L, initial dye concentration:75 mg L^{-1}, optimum contact time: 5 days, Temperature = 32 °C ± 2		Malachite green	7.0 g/L	

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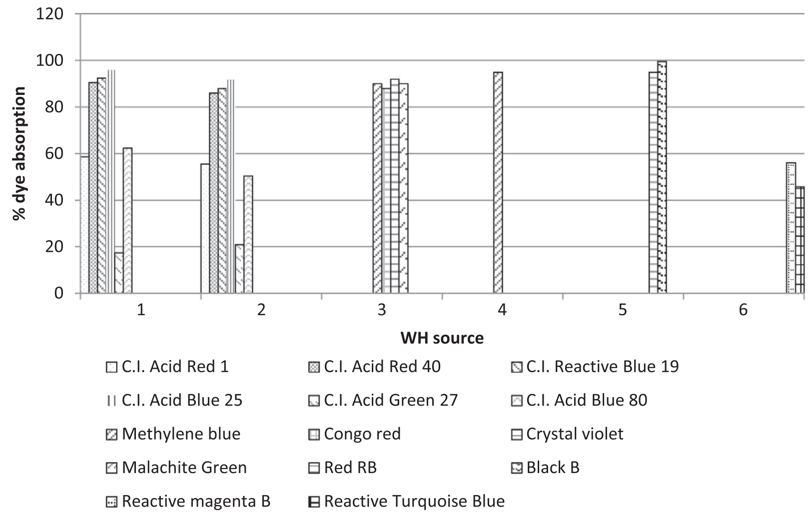

Figure 1 Percentage dye adsorption efficiency of different forms of water hyacinth vs. various dyes indicated in the graph. (1) Aminated raw E.C. with 12% sandene; (2) Scoured E.C.; (3) Aq. soln of WH; (4) Aq. soln of WH root; (50) WH in batch culture; (6) Activated carbon from WH.

3. Textile waste water treatment

Waste water is the major environmental issue of textile industries besides other minor issues like solid waste, resource wastage and occupational health and safety. Textile industry (and especially its part focused on the dyeing process) belongs among important sources of contamination responsible for the continuous pollution of the environment as the Textile wastewater contains substantial pollution loads in terms of chemical oxygen demand (COD), biological oxygen demand (BOD), total suspended solids (TSS), total dissolved solids (TDS) and heavy metals. These mechanisms can result from complexation, metal chelation, ion exchange, adsorption and micro precipitation (Rai et al., 2002). Phytoremediation is one of the waste water treatment methods by using plant based systems for removing the contaminants from various natural sources. To clean up the contaminated water, selection of an appropriate and efficient plant system is highly essential. Those plant systems should have high uptake of both organic and inorganic pollutants, grow well in polluted water and be easily controlled in quantitatively propagated dispersion. (Roongtanakiat et al., 2007).

In a list of various plant species used for phytoremediation attempts, water hyacinth was selected for the review because of its high pollutant removal and heavy metal removal efficiency, higher reproduction rate and tolerance of ecological factors. The use of water hyacinth in wastewater treatment systems has been increasingly reported and treatment regimens are developed as a result of successful project reports on its phytoremediation approaches. It has a huge potential for removal of the wide range of pollutants from wastewater (Chua, 1998; Maine et al., 2001; Sim, 2003; Mangabeira et al., 2004) and has the ability to grow in highly contaminated waters (So et al., 2003). It is also used to improve the quality of water by reducing the levels of organic, inorganic nutrients (Delgado et al., 1995) and heavy metals (Soltan and Rashed, 2003; Zhu et al., 1999).

Jie (1998) evaluated the removal of dyeing wastewater true colour (ADMI) by water hyacinth root powder. Pressure steam washes with water hyacinth root powder (SWHR) as adsorbent have effectively removed the true colour in dyeing wastewater. Dyeing wastewater has initial value of 666 ADMI, pH 2.0, SWHR 2.3 g/L, to 150 rpm, 24 h after the reaction, the temperature increased from 6 to 36 °C, its true colour removal rate improved from 68% to 78%. In a lab scale study, Mahmood et al. (2005) observed that water hyacinth has the capability to reduce the pH of textile waste water from alkaline to neutral, COD and BOD reduction in the range of 40–70%, total solids with a maximum reduction of 50.64%. The reduction in pH further favoured microbial action to degrade COD and BOD in wastewater.

Gamage and Yapa (2001) conducted a case study on the use of water hyacinth in treatment systems for textile mill effluents. The study was monitored for a period of one year on various pollution physiochemical parameters at the Veyangoda textile mill in Srilanka. The authors could achieve a substantial reduction in volatile solids 72.6%, dissolved solids 60%, suspended solids 46.6%, 75% BOD and 81.4% COD. An increase in organic nitrate ion concentration was seen suggesting nitrification of organic nitrogen in the medium. Similarly reduction in COD and pH was also observed in textile effluent collected from a textile industry in Bangladesh. 60 per cent of COD was reduced with the combination treatment of *Nostoc*, *E. crassipes* and *Pistia stratiotes* whereas 65% reduction was observed with the combination treatment of *Nostoc* and *E. crassipes* COD in glass containers. pH was reduced from 11.2 to 8.6. (Roy et al., 2010). Pramanik et al., 2011 examined the removal of dye and pathogenic bacteria from textile dye effluent of high strength COD by different adsorbents such as water hyacinth, tuberose pulp, sugarcane pulp and coconut pulp. The experimental results suggested that water hyacinth is the best natural adsorbent on the basis of removing dye and harmful pathogenic bacteria.

Kannadasan et al., 2013 studied the effectiveness of a natural coagulant derived from a cactus species for turbidity removal from dye industry effluent. Other parameters such as pH as well as colour were also studied. High turbidity removal determined indicates that cactus (Opuntia) and water hyacinth (*E. crassipes*) have the potential to be utilised for waste water treatment applications. Similarly Shah et al., 2010 observed water hyacinth as a remediation tool for dye effluent pollution. The authors reported significant decrease in the pH, TDS, conductivity, hardness, DO, BOD, COD, nitrate nitrogen and ammonium nitrogen in various concentrations of wastewater, where the water hyacinth performed well in 25–50% wastewater and not in 75–100% wastewater. Thus the authors concluded that the water hyacinth can be utilised for treating dye waste water after dilution.

Thus overall water hyacinth could reduce the alkaline pH to neutral and this reduction may be due to the absorption of nutrients or by simultaneous release of H^+ ions with the uptake of metal ions (Mahmood et al., 2005). According to Reddy (1981), the presence of plants in wastewater depletes dissolved CO_2 during the period of photosynthetic activity and an increase in DO of water, thus creates aerobic conditions in wastewater, which favours the aerobic bacterial activity to reduce the BOD and COD.

Gupta et al, compared the phytoremediation efficiency of three aquatic macrophytes water hyacinth, water lettuce and vetiver grass. Aquatic macrophytes were found to absorb nutrients with their effective root system. They are widely used to remove nutrients and heavy metals in the form of constructive wetlands or retention ponds because of their fast growth rate and ability to accumulate toxic materials. Phytoremediation of wastewater using floating aquatic macrophytes is an economic method to establish requires minimum maintenance and also improves biodiversity. The author concluded that many researchers have used water hyacinth, water lettuce and vetiver grass for the removal of water contaminants but their treatment capabilities depend on different factors like climate, contaminants of different concentrations, temperature, etc. The removal efficiency of contaminants like TSS, TDS, BOD, COD, EC, hardness, heavy metals, etc varies from plant to plant. Plant growth rate and hydraulic retention time can influence the reduction of contaminants.

4. Heavy metal removal

Among the various plants species group, aquatic macrophytes attain greatest interest in the field of phytoremediation. Aquatic macrophytes have great potential to accumulate heavy metals inside their plant bodies. These plants can accumulate heavy metals up to 100,000 times greater than the amount in the associated water. Therefore, these macrophytes have been used for heavy metal removal from a variety of sources (Mishra and Tripathi, 2008). Aquatic macrophytes such as water hyacinth, is one of the most commonly used plants in constructed wetlands because of its fast growth rate and large uptake of nutrients and contaminants (Rai, 2009; Yahya, 1990; Vesk et al., 1999; Tiwari et al., 2007). Dried water hyacinth roots (Schneider et al., 1995; Hasan et al., 2010; Elangovan et al., 2008), ash derived from water hyacinth (Mahmood et al., 2010; Kadirvelu et al., 2004) and the whole plant where the metals are taken up by the roots of the plant and translocated to the shoots and other plant tissues (Kelly and Guerin, 1995; Cunnigham and Berti, 1995; Jadia and Fulekar, 2009) were used by various researchers for the removal of heavy metals.

The adsorption efficiency of the water hyacinth in various forms to adsorb heavy metals is listed in Table 3, where most of the studies were carried out on the adsorption of heavy metals from the aqueous metal solution.

Mokhtar et al., 2011 reported *E. crassipes* as a hyperaccumulator for copper with an efficiency of 97.3% removal from an aqueous solution containing various concentrations of copper. (1.5, 2.5 and 5.5 mg/L of copper, for a period of 21 days). The roots and shoots tissues have shown an increase in concentration with a decrease in aqueous solution. Ajayi and Ogunbayo, 2012 studied the efficiency of water hyacinth in removing Cd, Cu and Fe from various wastewaters like textile, pharmaceutical and metallurgical in which it seems to be a good choice for removing cadmium but not so much for the removal of iron and copper. During the 5 weeks duration of the experiment, the removal of cadmium by the water hyacinth was 94.87% in textile wastewater, 95.59% in metallurgical wastewater and 93.55% in pharmaceutical wastewater. Jayaweera et al. (2008) concluded in their study that water hyacinths grown under nutrient-poor conditions are ideal to remove iron from wastewaters.

Schneider et al. (1995) studied the feasibility of dried water hyacinth roots for the removal of Pb^{2+}, Cu^{2+}, Cd^{2+} and Zn^{2+} ions from aqueous solution. The authors found that the dried roots and aerial parts of the water hyacinth are better biosorbents than the biomass of the bacterium *Mycobacterium phlei*, the yeast *Candida parapsilosis*, fungal *Rhizopus oryzae* strains, and acacia bark in terms of lead and copper uptake per dried mass of biosorbent. Hasan et al. (2010) reported that water hyacinth biomass (WHB) has shown high potential for the removal of hexavalent chromium from aqueous solution with Box–Behnken RSM design in which the R^2 value was 99.8%. But Elangovan et al. (2008) reported that among various aquatic plants studied water hyacinth efficiency was good with removal of Cr^{3+} rather than Cr^{6+}.

In a study by Kolawole (2001) of water hyacinth cultivation in a plastic bowl containing textile industry effluent the sample analysis has shown 70–90% removal of heavy metals like iron, lead, copper and chromium. Mahmood et al. (2005) reported that the water hyacinth plant could be able to remove metal ions like chromium, zinc and copper from the textile effluent collected from Lahore district, Pakistan. The feasibility of water hyacinth to treat wastewater from five textile effluent samples was investigated for a period of 96 h and it was observed that the water hyacinth containing textile effluent wastewaters have the potential to remove a maximum of 94.78% reduction in chromium, 96.88% in zinc and 94.44% reduction in copper.

5. Modifications in water hyacinth

To improve the efficiency of the biosorption property of water hyacinth various researchers have identified the tools like chemical modification and processing of the water hyacinth plants and its other parts. The acid/alkali treated water hyacinth was found to be efficient in removing various metal ions rather than the untreated plant materials. The ionisation of various functional groups present on the surface of the adsorbents in aqueous solution enable them to involve in cation binding with the metal ions and thus the acid and alkali treatment of the biomass was studied by several researchers in biosorption of metal ions. (Yao and Ramelow, 1997; Mahamadi and Nharingo, 2010a,b; Elangovan et al., 2008).

Table 3 Heavy metal adsorption capacity of the water hyacinth from different sources.

S. No.	Source of water hyacinth	Heavy metal	Source	Adsorption capacity	Optimised condition	Model	References
1	Dried water hyacinth – shoot and root	Cd (II) and Pb (II)	Aqueous solution	75% for Cd and more than 90% for Pb	Dosage of 5.0 g/L and pH 5.0	Second order kinetic	Ibrahim et al. (2012)
2	*Eichhornia crassipes* biomass	Pb(II), Cd(II) and Zn(II)	Aqueous solution	Sorption capacities (qm) of 26.32, 12.60 and 12.55 mg/g for Pb(II), Cd(II) and Zn(II) metal ions	(C0 = 10–60 mg/L), 3 h contact time, 30 °C, 2 g/L, 150 rpm and pH 4.84	Langmuir isotherm	Mahamadi and Nharingo (2010)
3	*Eichhornia crassipes*-type biosorbent	Zn (II) and Cd (II)	Batch binary system	0.65 mequiv./g maximum metal uptake	30 °C temperature and with non-uniform biosorbent grain sizes	Pseudo second-order kinetic model	Módenes et al. (2011)
4	Dry hyacinth roots (DHR)	Ar	Spiked drinking water sample	90% Arsenic removal	Concentration of 20 g/L DHR	Batch and continuous column experiments	Govindaswamy et al. (2011)
5	Water hyacinth plant	Fe	Fe rich wastewaters. In constructed wetlands	6707Fe mg/kg dry weight	–	Batch process (Fibre glass tanks)	Jayaweera et al. (2008)
6	Water hyacinth plant	Al	Al rich waste water in constructed wet lands	Highest phytoremediation efficiency of 63%	–	Batch process (Fibre glass tanks)	Jayaweera et al. (2007)
7	Water hyacinth plant	Mn	Synthetic wastewater in constructed wetlands	Phytoextraction mode of manganese removal	pH (6.2 to 7.1)	–	Kularatne et al. (2009)
8	Water hyacinth plant	Cu, Cd, Pb and Zn	Anaerobic upflow packed bed reactor with water hyacinth ponds	98% for Cd, 99% for Cu, 98% for Pb and 84% for Zn	10 days with a hydraulic retention time of one day	–	Sekomo et al. (2012)
9	Water hyacinth roots	Pb(II) ions	Aqueous solutions	–		Batch process pseudo-second-order model	Singha and Das (2012)
10	Water hyacinth plant	Zn and Cr	Aqueous solution	95% of zinc and 84% of chromium	–	–	Mishra and Tripathi (2009)
11	Water hyacinth plant	Fe, Zn, Cu, Cr and Cd	Aqueous solution	(>90%) of different metals during 15 days experiment	–	–	Mishra and Tripathi (2008)
12	Water hyacinth plant	Cd and Zn	Aqueous solution	Metal uptake by the plant was dependent upon the concentration of the metal and the duration of the exposure time	–	–	Hasan et al. (2007)
13	*Eichhornia crassipes* biomass	Pb(2+), Cd(2+) and Zn(2+) ions	Binary and ternary systems	Metal sorption followed the order			
	Pb(2+)>>Cd(2+)>>Zn(2+)	30 °C and pH 4.84	Langmuir Competitive Model (CLM),	Mahamadi and Nharingo (2010)			
14	Dried powdered stem and leaves of *Eichhornia crassipes* biomass	Cr6+	Batch sorption process	91.5181 mg/g maximum	pH 2.0, 40 °C, 300 mg/L meta concentration.	Langmuir sorption isotherm	Hasan et al. (2010)

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Table 3 *(continued)*

S. No.	Source of water hyacinth	Heavy metal	Source	Adsorption capacity	Optimised condition	Model	References
15	Activated carbon derived from *Eicchornia crassipes*	Hg^{2+}	Aqueous solution	28.4 mg/g	pH 5 for a particle size of 125–180 μm	Freundlich and Langmuir isotherm	Kadirvelu et al. (2004)
16	Water hyacinth plant	Cd and Zn	Aqueous metal solution	Cadmium in shoots – 148.0 μg/g roots – 2006.0 μg/g. zinc in shoots 1899.0 μg/g; in roots –9646.0 μg/g	–	–	Mohamad and Latif (2010)
17	Water hyacinth fibre	Cu and Zn	Aqueous solution	99.42 mg Cu2+ and 83.01 mg Zn2+ per 1 g biomass		Langmuir, Freundlich, Temkin and Dubinin–Radushkevich equations	Buasri et al. (2012)

FTIR and molecular modelling proves that a functional group like COOH could enhance the ability of the dry plant for mediating heavy metals through the interaction of the organic acids with the heavy metals (Osman et al., 2010; Ibrahim and Scheytt, 2007). Ibrahim et al. (2009) used molecular spectroscopic techniques to study the potential of the water hyacinth dry matter for the removal of heavy metals from wastewater. The authors observed that water hyacinth which is subjected to acetic acid is able to absorb acetate which finds its way to the cellulose of the plant. It was further suggested that the treated water hyacinth has the additional advantage that it reduces or even eliminates the diverse impact of the weed on the environment.

Similarly the higher efficiency of structurally modified water hyacinth in dyestuff removal through cyanoethylation and amidoximation was observed by Somboon and Bhavakul (2012). The hydroxyl functional group in the water hyacinth was chemically converted to the nitrile group by cyanoethylation reaction and part of the nitrile group was converted to the amino group by amidoximation and this modified water hyacinth (WH-AO) was able to adsorb acid blue 25 with higher efficiency on comparing with basic blue 9.

Kaur et al. (2013a) modified *Eichhornia* charcoal with sodium dodecyl sulphate and employed it as adsorbent for the removal of crystal violet from aqueous solution. Morphology and surface of the adsorbent were characterised by SEM, XRD and FTIR. Kaur et al. (2013b) studied the efficiency of *Eichhornia* charcoal to remove Congo red dye from aqueous solutions. Uddin et al. treated WH with hydrochloric acid and observed higher efficiency (dye uptake 0.26 kg/kg) in removing methylene blue from aqueous solution.

6. Advanced techniques in dye removal vs. water hyacinth

Although various physical, chemical and biological processes like reverse osmosis, flocculation, activated carbon adsorption, and microbial treatment are involved as dye treatment techniques, adsorption process plays a major role and was preferred as an promising and efficient method for the treatment of dyes and dye effluents. Various studies are reported in the literatures using different adsorbents like alumina, zeolite, and polyurethane foam etc (Módenes et al., 2013). The disadvantages of advance technology entail high operating cost, makes them ineffective to treat the wide range of effluents. Industrial and agricultural wastes (coir pith, sun flower stalks], rice husk, neem leaves, mango seed kernel, modified saw dust, peanut hulls, pineapple stem, banana pith, orange peel, guava leaf, wheat shell, wheat bran, egg shell, corn cobs and barley husk, treated wood shavings, almond, lemon peel, degreased coffee bean, rubber wood, jute fibre carbon) as low cost adsorbents are highlighted as an economic mode of dye effluent treatment nowadays. However the adsorption capacities of the low cost adsorbents mentioned above remain elusive and are not satisfactory. Thus still the search for simple, economic, ecofriendly, and highly effective adsorbents is continuing.

E. crassipes being one of the worst weeds in the world as a vigorous grower which is known to double its population within two weeks was worked out as a cheap and easily available adsorbent for dye and effluent treatment by various researchers. The weed and its various forms, modifications have been studied for increased efficacy. However much more detailed study on various textile dyes and different modified forms will establish water hyacinth as a simple, best and economic source for dye effluent treatment in the near future.

7. Conclusion

Water hyacinth, the worst aquatic weed was found to be highly impossible to eradicate from the water ways, though its quest for nutrients has given a possible way for its usage in phytoremediation. In the last few years great interest has been shown for the research of water hyacinth as a good candidate for pollutant removal or even as a bioindicator for heavy metals in aquatic ecosystems. In this present article the detailed biosorption efficiency of the water hyacinth in the removal of various pollutants present in textile waste water was enumerated. In conclusion, water hyacinth has high removal rates for various dye stuffs and heavy metals like iron (Fe), zinc (Zn), copper (Cu), chromium (Cr), cadmium (Cd), manganese (Mn), mercury (Hg) and arsenic (As) from aqueous solutions. Very few reports are available in the literature on the direct application of water hyacinth and its derived products in removal of dyes and heavy metals from textile effluent as well as from wastewater. This may be due to the complexity of the textile effluent and its wastewater with the various number of chemicals being used in the dyeing and processing units. More research is needed to achieve a greater efficiency in contaminant removal with respect to certain modifications in its functional group or various treatment procedures of the plant and its parts that can be focused upon in near future.

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