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REVIEW ARTICLE

The efficiency of *Eichhornia crassipes* in the removal of organic and inorganic pollutants from wastewater: a review

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Abstract Water is a basic necessity of life, but due to over-extraction and heavy input of nutrients from domestic and industrial sources, the contamination level of water bodies increase. In the last few decades, a potential interest has been aroused to treat wastewater by biological methodologies before discharge into the natural water bodies. Phytoremediation using water hyacinth is found to be an effective biological wastewater treatment method. Water hyacinth (*Eichhornia crassipes*), a notorious weed, being the most promising plant for removal of contaminants from wastewater is studied extensively in this regard. It has been successfully used to accumulate heavy metals, dyes, radionuclides, and other organic and inorganic contaminants from water at laboratory, pilot, and large scale. The plant materials are also being used as sorbent to separate the contaminant from water. Other than phytoremediation, the plant has been explored for various other purposes like ethanol production and generation of biogases and green manures. Such applications of this have been good support for the technocrats in controlling the growth of the plant. The present paper reviews the phytoremedial application of water hyacinth and its capability to remove contaminants in produced water and wastewater from domestic and isndustrial sources either used as a whole live plant grown in water or use of plant body parts as sorbent has been discussed.

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Introduction

Water is an abject necessity for any kind of life on the earth. Other than drinking, bathing, and domestic uses, water is used in agricultural and industrial sectors. A large amount of wastewater is generated after domestic and industrial uses, which is discharged either directly or after partial treatment, to the nearby water bodies that adds a large number of toxic contaminants to the reservoir (Mishra et al. 2015). Therefore, considerable attention has been given to develop treatment methodologies and those commonly used include oxidation and reduction (Bissen and Frimmel 2003), electrochemical methods (Pirnie 2000), ion exchange (Wang et al. 2000), chemical precipitation (Ladeira et al. 2002), coagulation (Sancha 2006), membrane filtration (Ravenscroft et al. 2009; Litter et al. 2010), and biological processes (Park et al. 2010). Most of these methods have limitations to some aspects that have been understood to include incomplete treatment, high energy and chemical requirements, high operational and maintenance costs, and requirement of proper disposal methodologies for toxic waste generated (Weis and Weis 2004). As a result of it, phytoremediation could be the possible potential method of providing an alternative to current treatment technologies for wastewater (Liu et al. 2007; Paz-Alberto and Sigua 2013). It is eco-friendly and potentially cost effective and involves the use of plants like *Brassica* sp. *Thlaspi caerulescens*, *Aeolanthus biformifolius*, and *Haumaniastrum katangense* (Prasad 2003) and aquatic macrophytes such as duckweeds (*Lemna* sp. and *Spirodella* sp.), water hyacinth (*Eichhornia* sp.), water lettuce (*Pistia* sp.), and small water fern (*Azolla* sp.) which has demonstrated a good ability to absorb and concentrate many toxic contaminants from aquatic environments (Mishra and Tripathi 2009). This technology is based on the unique and selective contaminant uptake capabilities of plant root systems, together with the translocation, bioaccumulation, phytostabilization, rhizodegradation, rhizofiltration, phytovolatilization, and degradation within the entire plant body (Tangahu et al. 2011). The biological removal of contaminants from solution by biomaterials occurs through interactions with functional groups present in proteins, lipids, and carbohydrates found in cell walls (Mahamadi and Nharingo 2010; Penfound and Earle 1948). Among the various plants species group, aquatic macrophytes showed great potential in the field of phytoremediation (Priya and Selvan 2014). In the recent advances, Kumar et al. (2008) studied the heavy metal (Cd, Co, Cu, Ni, Pb, and Zn) accumulation in *Ipomoea aquatica*, *Typha angustata*, *Eichhornia crassipes*, *Echinochloa colonum*, *Nelumbo nucifera*, *Hydrilla verticillata*, and *Vallisneria spiralis*. The authors found that the maximum Zn accumulation was in *E. crassipes* than the other plants. Moreover, the *E. crassipes* stem and leaves showed maximum accumulation of metals like Zn and Cr in comparison to the other plants' stem and leaves. The authors have concluded that three native aquatic plant species *T. angrustata*, *E. crassipes*, and *I. aquaitca* accumulated heavy metals in much higher concentrations and were more efficient in uptake of heavy metals. Mishra et al. (2008) studied the phytoremediation of mercury and arsenic using *E. crassipes*, *Lemna minor*, and *S. polyrrhiza* from a tropical open cast coalmine effluent. The study reported that the removal capacities of these macrophytes were in the order of *E. crassipes* > *L. minor* > *S. polyrrhiza*. In another study, the phytoremedial potential of *Typha latifolia*, *E. crassipes*, and *Monochoria hastate* was assessed by Hazra et al. (2015) and found to have a good bioconcentration factor (BCF) against heavy metals. The authors reported that *E. crassipes* showed maximum BCF for metals compared to the other two plants. Sung et al. (2015) studied the effect of *E. crassipes* and *Ceratophyllum demersum* for nutrient removal on both wet soil and water environments and reported that concentration of nitrogen and phosphorus reduced more in the presence of *E. crassipes* compared to others. Also, it has been reported to be a good candidate for biological filtration system (Kanawade and Gaikwad 2011; Ibrahim et al. 2012). Therefore, based on the literature review, water hyacinth has been found to be an effective candidate for phytoremediation of pollutants from wastewater and wetland.

A few number of review articles have been published in the recent years related to the removal of pollutants from an aqueous medium using water hyacinth. Mahamadi (2011) has reviewed the application of water hyacinth as biosorbent and described its various aspects like raw dried root, activated carbon, and acid-/alkali-treated biomass for metal sorption and recovery. He concluded that the plant biomass has excellent sorption capability for several metals ions. Priya and Selvan (2014) have written a review on the adsorption of dyes from textile effluent using water hyacinth body parts as adsorbent. Based on the literature available, it has been concluded that the plant has good potential to remove heavy metals and dye stuffs from textile effluent. Balasubramanian et al. (2014) have written a review about the ecological significance, management, and control of the plant water hyacinth and concluded that there is no any holistic approach that could describe the species effect on soil nutrient flux, crop production, and microbial biomass, so far either in India or elsewhere. Rezania et al. (2015b) have reviewed the various applications of water hyacinth and reported that plant can be used for wastewater treatment, biofuel production, paper production, furniture making, production of fertilizers, and animal feed. They also suggested that the use of plant would be environmentally sustainable and cost effective. Later, in another review, Rezania et al. (2015a) described the phytoremediation potential of water hyacinth for the removal of organic and inorganic pollutants from various types of wastewater and suggested that plant could be a suitable candidate for treatment and control of various industrial wastewaters at large scale.

Despite of these available review articles, a comprehensive study of pollutant removal using water hyacinth as biosorbent and phytoremediation plant implemented at laboratory and large scale is not available along with its other applications, problems, and prospects associated with this treatment method. Therefore, in this paper, a review study has been explored related to phytoremediation and biosorption potential of water hyacinth for various inorganic and organic nutrients from various types of wastewater at laboratory- and large-scale applications. Along with the other applications of the plant in different industries, the problems related to its cultivation have been described with available mitigation prospects.

Water hyacinth is a perennial, mat forming, invasive species and rooted macrophyte, belonging to the pickerelweed family pontederiaceae, considered to be originated from Brazil in South America, has extremely rapid proliferation, and congests growth in polluted water bodies found abundantly in Southeast Asia (including India, China, Pakistan, and Bangladesh), Africa, North America, Nigeria, New Zealand, and the Pacific (Ndimele et al. 2011), as shown in Fig. 1. The plant has high multiplication rate: it could double in number within 7 days in conditions of high temperature and humidity (Gunnarsson and Petersen 2007). According to Abdelhamid and Gabr (1991), about 140 t of plant dry matter/hectare per year are produced. The plant could prolifically propagate though stem fragments and seeds. The seeds can remain viable for 6 years, and the pollination in the plant is anemophily, i.e., the distribution of the plant material occurs by winds (Aweke 1993). The plants flourish in nutrient-rich water bodies and in mud rich in nutrients near shallow shores. The plant has an

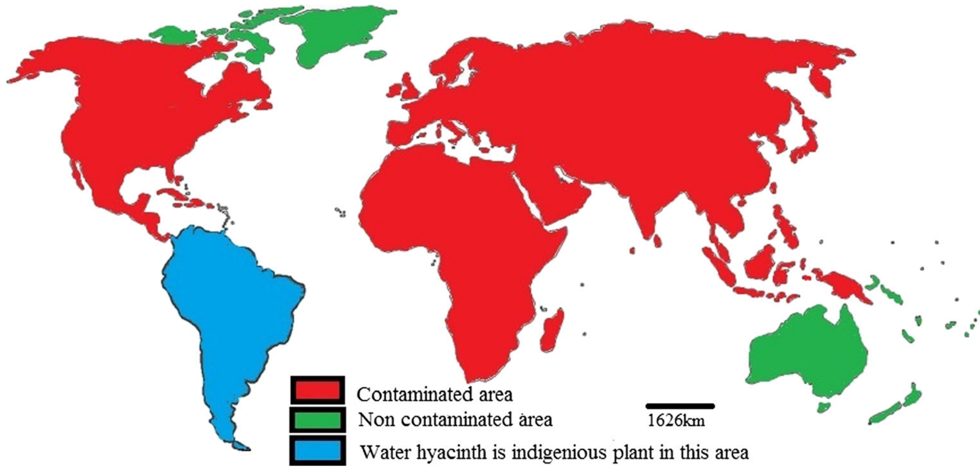

Fig. 1 Worldwide geographical presence of water hyacinth (Rezania et al. 2015a)

excellent uptake potential for nutrients and other chemicals from the environment. Poddar et al. (1991) reported 1.78% (db) nitrogen content in water hyacinths growing in marshy land where the nitrogen level in the water was only 2.40 mg/L. The accumulation of nutrients was found to be lower in the root and stem than the nutrient content in the leaves.

Phytoaccumulation capability

Phytoaccumulation is a process of uptake of contaminants by the plants roots, adsorption onto roots, precipitation within the root zone, and translocation/accumulation in the shoots and leaves. The water hyacinth, and other aquatic plants, root structures provide an appropriate environment for the growth and function of aerobic bacteria in sewage systems. Aerobic bacteria utilize the nutrients and produce inorganic compounds which in turn supply food for the plants. The plants have been investigated to accumulate both organic and inorganic contaminants in wastewater (Paz-Alberto and Sigua 2013). Jayaweera et al. (2008) studied the Fe removal mechanism of water hyacinth in batch-type constructed wetlands. The authors reported that plant showed highest phytoremediation efficiency of 47% in synthetic wastewater enriched with an initial concentration of 9.27 Fe mg/L during optimum growth conditions in 6 weeks. They found that the Fe removal was mainly due to rhizofiltration and chemical precipitation of Fe $(OH)_3$ and Fe_2O_3. In addition, a key mechanism, active efflux of Fe back to growth medium at intermittent period was observed by them in water hyacinth to prevent the Fe phytotoxicity. In another study, Kularatne et al. (2009) studied the removal mechanism of Mn by water hyacinth and reported that phytoextraction is mainly responsible for removal of Mn, while the chemical precipitation mechanism was absent due higher solubility of metal. The stepwise procedure performed for phytoaccumulation of nutrients from contaminated water using aquatic plant has been shown in Fig. 2.

According to Rezania et al. (2016), water hyacinth is a free-floating aquatic plant, in which metal uptake (through adsorption) by roots is translocated to different parts of the plant

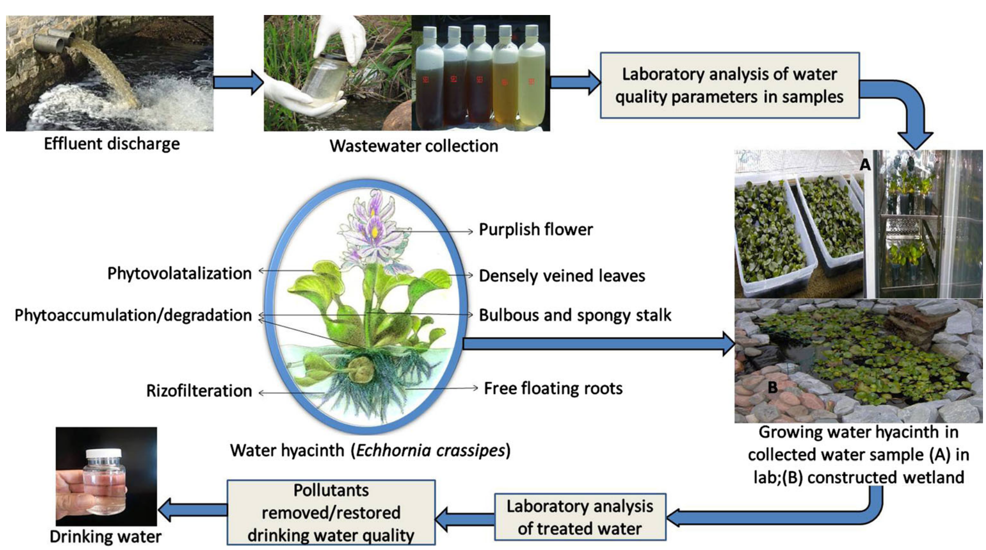

Fig. 2 Stepwise procedure of wastewater treatment using water hyacinth

(especially the aerial part), while the absorbed organics are utilized in cellular metabolic activities. Pollutant removal by this aquatic plant depends on its nutrient assimilative capacity and the biochemical/physico-chemical processes occurring within the system (Sooknah 2000). The biodegradation of substrate molecules that takes place through respiratory pathways requires the availability of proteins, enzymes, and electron acceptors in the plant. This necessitates to investigate the change in molecular substances involved in interlinked respiratory pathways. Li et al. (2015a) studied the role of proteomics to elucidate the molecular mechanism of eutrophic water purification using *E. crassipes*. The authors reported that the amount of proteins which were involved in N and P metabolism, in plant, significantly increased with increasing the N and P concentrations and resulting gain in plant biomass when the photosynthesis limiting factors (light, temperature, CO_2 concentration, and water supply) were maintained stable. In addition, the proteins regulated the synthesis and release of algal growth inhibitory allelochemicals that restricted the growth of algae in water used for cultivation of water hyacinth. In another study, to understand molecular changes in water hyacinth on exposure to Cd stress, Li et al. (2015b) found that physiological and metabolic proteins were affected on exposure to Cd stress. However, analog proteins were induced to retain the corresponding functions: water hyacinth could regain biomass and much faster than *Pistia stratiotes*. In addition, some stress-resistant proteins like heat shock proteins (HSPs) and amino acid such as prolin and post translational modifications factors were found to be engaged in protection and repair of physiological and metabolic proteins. Consequently, the antioxidant enzymes significantly removed the excess reactive oxygen species which were formed in the plant body during Cd exposure.

Phytoaccumulation of inorganic pollutants by water hyacinth

Mishra and Tripathi (2008) while studying the removal efficiency of *P. stratiotes*, *S. polyrrhiza*, and *E. crassipes* for heavy metals (Fe, Cu, Zn, Cr, and Cd) reported that the water hyacinth was more efficient for the removal of selected metals than the other two plants. Later, in another study, Mishra and Tripathi (2009) demonstrated the accumulation capability of water hyacinth in synthetic produced water having Cr and Zn ions in the concentration range of 1–20 mg/L. The authors found that the plant could remove both metals by 90–95% with no morphological toxicity on the plant at all studied concentrations and the environment was efficient and safe for plant growth when planted for the removal of Zn and Cr from contaminated wastewater in the large-scale application. Another study done by Espinoza-Quinones et al. (2008), on the removal of ionized Cr^{+3} and Cr^{+6} from produced water by *E. crassipes*, *P. stratiotes*, and *Salvinia auriculata*, found that water hyacinth had shown maximum removal efficiency for Cr^{+3} while for Cr^{+6}, it was minimum compared to the other plants. Wolverton et al. (1978) studied the bioaccumulation of Cd ions in water hyacinth. The plant leaves were reported to be useful for bioaccumulation of high Cd concentration. The work was modified by Swain et al. (2014), who studied the removal capability of water hyacinth for Cd and Cu ions and found that at all studied concentrations, the highest concentration of Cd (230.39 mg/kg on the basis of dry weight) accumulated in the roots, while Cu (2314.2 mg/kg on the basis of dry weight) was accumulated in stems within the same duration. Therefore, it was recommended that the plant can be efficiently used to treat water contaminated with multimetal ions such as Cu and Cd. Misbahuddin and Fariduddin (2002) studied the arsenic (As) removal potential of water hyacinth on laboratory scale. The researchers used As (400 μ/L) solution to grow 0.5–0.6 kg plants and found that plant could remove ~100% arsenic from the solution. Later, the water hyacinth potential for the removal of arsenic was examined by Alvarado et al. (2008) with real contaminated water. They studied the removal of arsenic from water by water hyacinth (*E. crassipes*) and duckweed (*L. minor*) and reported that removal efficiency of water hyacinth was higher than duckweed. The removal rate for water hyacinth and duckweed was 600 mg As/ha day^{-1} with 18% removal recovery and 140 mg As/ha day^{-1} with a removal recovery of 5%, respectively. Odjegba and Fasidi (2007) investigated the removal efficiency of water hyacinth in produced water contaminated with Ag, Cr, Cu, Cd, Hg, Ni, Pb, and Zn ions. The plant was found to have differential accumulation and tolerance capability in the order of Zn > Cr > Ag > Pb > Cd > Cu > Ni > Hg. Mukherjee and Mondal (1995) carried out the work on the removal of Pb ions from synthetic spiked water having an initial concentration of 0.5–10 mg/L, by water hyacinth, and had found that the plant could successfully remove 85–95% of Pb ions within 10 days. Other than metals removal study, Haller et al. (1974) studied the effect of salinity on growth of *E. crassipes* and reported that the salt concentration of 2.5% is toxic to the plant. Later, Casabianca and Laugier (1995) modified the earlier findings and reported that the *E. crassipes* could grow well in saline water of 4 g/L. Although, biomass production was not observed in the salinity of 6 g/L, but the plant remain viable at salinity concentration between 6 and 8 g/L. The behavior of water hyacinth has been successfully analyzed against radioactive isotopes like ^{137}Cs and ^{60}Co by Saleh (2012). The author reported that the accumulation rate of radiocesium from produced water is inversely related to the initial activity content and directly related to mass of plant and duration of light (Saleh 2012). Kelley et al. (1999) studied the sorption of Eu(III) by water hyacinth and reported the 26% removal of the reactive metal within 48 h of exposure. Based on the earlier studies, it could be suggested that the plant could be a potential candidate for removal of various radionuclides.

Phytoaccumulation of organic pollutants

Xia and Ma (2006) studied the removal of a phosphorus pesticide ethion using water hyacinth and reported that plant contributed 69% (uptake and phytodegradation) removal of ethion. However, the researchers also found that the concentration of accumulated ethion in shoots and roots of the plant decreased by 55–91 and 74–81%, respectively, after a 7 day growth of plant in ethion-free culture solutions. Based on their observations, the authors concluded that the plant uptake and phytodegradation was a dominant process for removal of ethion. The present observations were also supported by Xia (2008) who had worked on the removal of organochlorine pesticide of dicofol using water hyacinth. The researcher reported that when the plant was grown in a dicofol-free medium after successful removal of 95% of dicofol from contaminated water: the dicofol content reduced to 41–53% in plant body in 7 days due to phytodegardation. Hence, it has been suggested that the plant could be an efficient, economical, and ecological alternative for development as a phytoremediation system for organochlorine pesticide of dicofol contaminated water. In another evidence reported by Nesterenko-Malkovskaya et al. (2012), they had studied the removal of organic compound naphthalene from the contaminated water and reported that the plant could significantly remove the naphthalene by ~100%. They also observed that the water hyacinth devoid of rhizospheric bacteria reduced significantly naphthalene concentration in water by 45%. This result clearly indicates that that the rhizospheric bacteria play an important role in accumulation and removal of organic components from the contaminated water. Lu et al. (2014) studied the removal of tetracyclines (TCs) and Cu by water hyacinth and reported that Cu/TCs could effectively be removed by 80% when the plant was grown in the nutrient solution.

The accumulation capability of water hyacinth for various inorganic metals and organic compounds, the concentration up to which a plant could grow, and gain biomass within particular period have been listed out in Tables 1 and 2. From Table 1, it is clear that the plant could successfully remove Cr, Zn, Cu, Ag, Pb, and As ions by 80–100% and also did not show any harmful morphological symptom, while it is found to be less efficient in accumulating Ni, Hg, Cs, and Eu ions. The plant showed morphological toxicity symptoms like leaf size decrease and chlorophyll loss against these metals. Other than freshwater, it can also survive and has potential to remove pollutants in saline environment. Moreover, the plant has also been found to be good accumulator of organic compounds up to 80–100% with no morphological change, as shown in Table 2. However, research is still required to investigate the tolerance capability of plant against various toxic organic acids, hydrocarbon compounds, and pharmaceutical compounds at higher concentrations. Based on these earlier studies, it has been revealed that the organic pollutants are phytodegraded within the water hyacinth, which would be a sustainable and cost-effective method to get rid of organic contaminants.

From the mentioned Tables 1 and 2, it has been revealed that the use of water hyacinth could be a good and potential candidate for purification and removal of organic and inorganic contaminants like pesticides, pharmaceuticals, metals, and radioactive isotopes from the domestic, agricultural, and industrial wastewater.

Mechanism of bioadsorption of pollutants by water hyacinth

Water hyacinth has drawn attention as a plant that capable to remove contaminants, including toxic metal ions from shallow water bodies. The mechanism of biosorption process has been shown in Fig. 3. The plant material like dried root, activated carbon, and ash derived from plant, acid-/alkali-treated plant, and biochar derived from plant of water hyacinth has been examined by researchers for the sorption of contaminants from wastewater. These biosorption materials have functional groups like alcohol, ketones, and aldehydes and other groups on their surface. The contaminants in the aqueous solution bind through those functional groups on the biosorbent surfaces at particular pH, and precipitation occurs (Ofomaja and Ho 2007). The biosorption was influenced by pH, dose of biomass, concentration of contaminants, and temperature. Several researchers have therefore studied the biosorption of different types of contaminants, at various concentration and environmental conditions from the aqueous medium using water hyacinth plant materials that are listed in Tables 3 and 4.

Bioadsorption of inorganic pollutants by water hyacinth

Sinha et al. 2003 studied the sorption of fluoride using carbonized and non-carbonized water hyacinth at temperature (25–45 °C). The authors reported that the process was endothermic in nature and carbonized plant material had better removal efficiency than the non-carbonized. Elfeky et al. (2013) studied the biosorption of Ni and Cd using the water hyacinth dried root thin film and have reported that the plant root has significantly high ability to remove the selected metals by 55–70%. Similar investigations have been done for the sorption of other metals using water hyacinth by different researchers around the world. Rmalli et al. (2005) studied the biosorption of arsenic from the 200 μg As/L contaminated water by water hyacinth dried root and reported the 93 and 95% removal of As(III) and As(V) within 60 min of

Table 1 Phytoaccumulation of inorganic contaminants from produced water by water hyacinth

S. no.	Pollutants	Experimental condition	Maximum removal efficiency/uptake	Remarks	References
1	Fe, Zn, Cu, Cr, and Cd	• Initial concentration 1, 2, and 5 mg/L • 100 g of healthy plant • Contact time 15 days	>90%	• No toxicity or reduction in growth	Mishra and Tripathi (2008)
2	Chromium (Cr) and zinc (Zn)	• Initial concentration 1, 5, 10, and 20 mg/L • Contact time 11 days	• Removal: Zn (95%) and Cr (84%)	• Zn accumulation is better in roots than leaves • No Zn toxicity	Mishra and Tripathi (2009)
3	Copper (Cu) and cadmium (Cd)	• Initial Cu concentration (0.35, 0.70, and 1.05 mg/L) and Cd concentration 0.27, 0.54, and 0.81 mg/L	90%	• Highest accumulation of Cd in roots, while Cu in stems	Swain et al. (2014)
4.	Arsenic (As)	• Initial As concentration 400 μ/L • 0.5–0.6 kg healthy plant • Contact time 6 h	100%	•Effectively removes As	Misbahuddin and Fariduddin (2002)
5	Lead (Pb)	• Pb concentration 0.5–12 mg/L • 400 g healthy plant • Contact time 10 days	• Removal: 85–92%. • Uptake: 7.27–148.8 mg/kg day^{-1}	• No pH dependency for Pb sorption	Mukherjee and Mondal (1995)
6	Cadmium (Cd)	Initial concentrations 0.06–10 mg/L	82–92%	Cd accumulation increased with increase in initial concentration in solution	Prakash et al. (1987)
7	Cd, Pb, and strontium (Sr)	• Initial concentration 5, 25, 50, and 100 μg/cm^3 • Healthy plant • Contact time 20 days	By root (50%) and leaves (30%)	• Calcium oxalate crystal in plant increased in exposure to Sr • The plants intoxicated at 100 μg/cm^3 after 2 days .	Mazen and Maghraby (1998)
8	Ag, Cd, Cr, Cu, Hg, Ni, Pb, and Zn	• Initial concentration 0, 0.1, 0.3, 0.5, 1.0, 3.0, and 5.0 mM • 44.7 g healthy plant • Contact time 21 days	Tolerance percentage for Ag (53.35%), Cd (48.52%), Cr (56.39%), Cu (47.59%), Hg (16.52%), Ni (26.30%), Pb (52.50%), and Zn (85.50%)	• Poor accumulator of Hg	Odjegba and Fasidi (2007)
9	Radioisotopes cesium (^{137}Cs)	• Initial concentration 30–260 Bq/mL • 5–15 g healthy plant • Contact time 21–48 h	33.0%	• A spiked solution of pH ≈ 4.9 was found to be the suitable medium for the treatment process	Saleh (2012)
10	Europium (Eu(III))	• Initial concentration 3.3 × 10^{-4} M • Healthy plant • Contact time 48 h	• Removal: 26% • Uptake: 8.7 × 10^{-5} mol/g dry root	•Eu(III) was concentrated mostly on the external surface of the roots	Kelley et al. (1999)
11	Salinity (NaCl)	• Initial salinity 2.1, 2.9, 4, 6, 9.2, and 13.7 • 600 g plant • Contact time 28 days	–	• Plant yield inversely linked to salinity • Biomass yield stopped at salinity 6 g/L and the irreversible damage in plant at salinity above 8 g/L	Casabianca and Laugier (1995)

Table 2 Phytoaccumulation of organic contaminants from produced water by water hyacinth

S. no.	Pollutants	Experimental condition	Maximum removal efficiency/uptake	Remarks	References
1	Dicofol	• Initial concentration 1 mg/L	• Removal: 95%	• No morphological change in plants	Xia (2008)
		• 10 g healthy plant	• Uptake: 0.05 mg/kg or 53.24 μg/g	• Dicofol accumulation in the plant reached maximum in 72 and 168 h for non-sterile and sterile treatment, respectively	
		• Contact time 3 weeks			
2	Ethion	• Initial concentration 0.01, 0.1, and 1 mg/L • 500 g healthy plant	69%	• No morphological change in plants when exposed to 1 mg/L ethion • Ethion accumulation in plants decreased by 55–91% in shoots and 74–81% in roots after 1 week of incubation in culture solutions without ethion	Xia and Ma (2006)
		• Contact time 3 weeks			
3	Naphthalene	• Initial concentration 15 mg/L	• Removal: 100%	• Plants, decoupled of rhizospheric bacteria, reduced naphthalene concentration by 45% during 7 days	Nesterenko-Malkovskaya et al. (2012)
		• 4–5 g healthy plant	• Uptake: 637 μg/g^{-100} h	• No plant toxicity when exposed to 50 mg/L naphthalene	
		• Contact time 9 days		• Biphasic uptake, i.e., rapid first phase of 2.5 h and slower second phase of 2.5–225 h	
4	Tetracyclines	• Initial concentration 15 mg/L	• 0.013–0.258%	Removal of TCs better suited in water co-contaminated with Cu	Lu et al. (2014)
		• Healthy plant			
		• Contact time 20 days			
5	Chlorpyrifos	• Initial concentration 0.1, 0.5, and 1.0 mg/L • 70 g healthy plant	• Removal: 100, 91, and 82% at 0.1, 0.5, 1 mg/L, respectively	• 3.89–4.88-fold higher removal rate in the presence of plants than without plants	Anudechakul et al. (2015)
		• Contact time 10 days	• Uptake: root 310 ± 28 mg/kg, stem 180 ± 12 mg/L, and in leaves 295 ± 25 mg/L for an initial concentration of 1 mg/L		
6	Textile dyes (red RB and Black B)	• Initial concentration 10–50 mg/L • Healthy plant	95% with red RB and 99.5% with Black B	• Textile dyes removed effectively from the wastewater	Muthunarayanan et al. (2011)
		• Contact time 144 h			

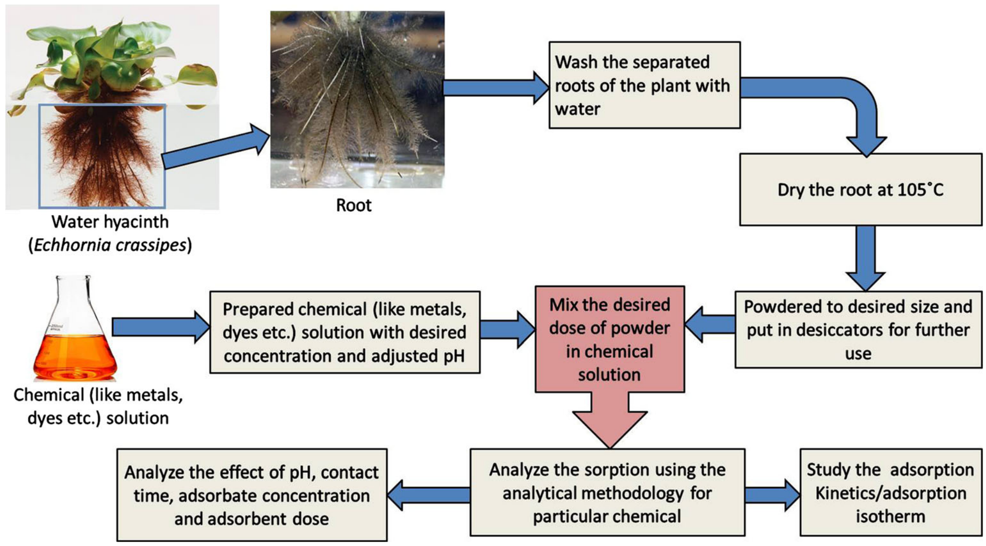

Fig. 3 Stepwise procedure of sorption using water hyacinth dried root

contact time. Further, Zheng et al. (2009) reported that the 20 g of dried root of water hyacinth could adsorb >75% of Cu(II) from 30 mg/L contaminated water. As mentioned, Bhainsa and D'Souza (2001) had studied the sorption of radioactive metal uranium using dried root of the plant. The authors reported that the sorption data well fitted to both Langmuir and Freundlich isotherm. The reaction was found to be free from the influence of temperature, and dried root of the plant removed 90% of uranium rapidly. This finding provides an opportunity to researchers for further study to understand the removal potential of plant for other reactive metals, which could prove to be a cost-effective and sustainable technique.

From Table 3, it has been clear that dry root of the plant proved to be a good adsorbent for metals and could remove up to 90% various metal ions. The metals like Ni, to which live plant acted as a poor accumulator but when dried root of plant used as adsorbent, showed good adsorbent capability of 55%. About 90% adsorption efficiency for radioactive uranium indicates that the plant part used as adsorbent could be a better effective water treatment technique. The parameters like pH, adsorbent and adsorbate dose, and temperature are found to have significant impact on the adsorption process.

Bioadsorption of organic pollutants by water hyacinth

The biomaterial has also been investigated for removal of organic pollutants such as phenol and dyes (acidic and basic) from the aqueous solution. Uddin et al. (2007) studied the adsorption of phenol at initial concentration of solution varying from 40 to 110 mg/L using 0.75 g/150 mL of water hyacinth ash. The authors reported that the data obtained during analysis was best fitted to both pseudo-first-order and pseudo-second-order kinetic models and the phenol were removed up to 90–95%. In another study, El Zawahry and Kamel (2004) performed the experiment for the removal of azo and anthraquinone dyes from solution using dried root. The authors found that the kinetic data well fitted to Freundlich isotherms: the adsorption model indicated the adsorption completed within 10 min leaving dye-free solution. Rajamohan (2009) studied the removal of acidic dye Congo red (100 mg/L) using 0.1 g of activated dried root of the water hyacinth. The authors reported that the effective removal at pH 6 with maximum uptake of 46.15 mg/g and the equilibrium was reached in about 3 h contact time. The another study reported by Low et al. (1995), studied the sorption of basic dyes methylene and Victoria dye from solution using dried root of plant and reported that the 48–98% removal of methylene blue and 145.4 mg/g uptake of Victoria dye. Later, Soni et al. (2012) studied methylene blue dye adsorption using the plant dried root by varying the parameters such as pH initial concentration of dye, adsorbent dose, and contact time. The authors reported that the maximum uptake of the dye was 8.04 mg/g with 95% removal. Moreover, Guerrero-Coronilla et al. (2015) reported the 98% removal of amaranth dye while studying the sorption kinetics of dye by using dried roots of water hyacinth.

In Table 4, it can be observed that the plant biomass shows more affinity to remove basic dyes compared to acidic dyes at lower pH. The anions are easily adsorbed at lower acidic pH, while less adsorption of the cationic dye was observed at same pH since surface charges of sorbents remain positive at that pH range (Priya and Selvan 2014). The cations show good adsorption at higher pH. Thus, acidic dyes adsorb better at higher pH and basic dyes at lower pH (Aboul-Fetouh et al. 2010).

Phytoremediation potential of water hyacinth on industrial scale

After investigation of removal efficiency water hyacinth for contaminants from aqueous solution, the plant has been analyzed on a large scale by several researchers to treat domestic and industrial wastewater samples, presented in Table 5. Zimmels et al. (2006), on the basis of their investigation of sewage wastewater treatment capability of water hyacinth and water lettuce on laboratory and pilot scale, observed that the plants were capable of lowering major water quality parameters like total suspended solids (TSS), biochemical oxygen demand (BOD), dissolved oxygen (DO), chemical oxygen demand (COD) to levels required by national and local guidelines for irrigation water, with overcoming changes in the feed within the test time. Later, Ajayi and Ogunbayo (2012) reported that the water hyacinth could significantly remove the nutrients form textile, metallurgical, and pharmaceutical wastewaters. The authors found that the percentage of removal of BOD was in order of metallurgical > textile > pharmaceutical wastewater, while improvement in DO was in order of metallurgical > pharmaceutical > textile wastewater and for lowering nitrate–nitrogen was in the order of textile > metallurgical > pharmaceutical wastewater. Lagos et al. (2009) studied the removal of tertiary colors and other nutrients by water hyacinth in wastewater of kraft paper industry and found that the plant was able to grow, remove, and balance nutrients even in undiluted wastewater. The other applications were found in oil, piggery, dyes, and electroplating industries where the water hyacinth has proved to be a good candidate to remediate of nutrients from wastewater samples. Costa et al. (2000), while working on treatment of piggery waste, observed a significant removal of phosphorus when 75% of the top surface area of water bodies containing wastewater was covered by plant. Sooknah and Wilkie (2004) studied the potential of three floating aquatic macrophytes water haycinth, pennywort, and water lettuce to improve the water quality of anaerobically digested flushed dairy manure. The authors reported that the pennywort and water lettuce could not sustain and had limited growth due to salinity, while significant growth was observed for water hyacinth which removed 90–100% of nitrogen and phosphorus in a batch culture. Later, Cheng et al. (2010) used both live plants and dried straw of water hyacinth against piggery wastewater and found that the straw behaved as a good adsorbent towards phosphorus. Similarly, Sahu et al. (2007) were working on *Spirodela polyrhiza* and *E. crassipes* and reported that the plants were capable to treat the wastewater from electroplating industries. Shah et al. (2010) reported water hyacinth as good phytoremediation species to treat dye industry effluents. The researchers found significant reduction (by 100%) in the pollution load in dye effluents after treatment with water hyacinth. Hadiyanto and Soetrisnanto (2013) studied the removal efficiency of water hyacinth, water lily, and alga (*Spirulina* sp.) to reduce the COD, nitrogen, and phosphorus in palm oil effluent. The authors reported that the plants could significantly reduce the contaminants by 90% and were found to be better in removing nitrogen than the alga. Furthermore, study on the removal of effluents from refinery and petrochemical industry was done by Ugya and Imam (2015) using water hyacinth and reported that the plant could significantly reduce heavy metals ions (Cd, Hg, Zn, Mn, Pb, and Ag) by 90–100% and COD by 50% from the wastewater. In another study, Ugya et al. (2015) obtained the mean biotranslocation factor above one for Mn, Zn, Ag, Cd, Hg, and Pb ions.

The plant has also been proved to be a good candidate for the removal of nutrients from paper and pulp industries as reported by Verma et al. (2005). The authors found that that 80.3% of Pb and 73.4% of Zn ions were successfully removed during biosorption at 20% effluent concentration. The heavy metal removal efficiency of water hyacinth has been investigated in mining wastewater by Romanova et al. (2016) and Prasad and Maiti (2016). In both studies, the authors reported the maximum accumulation of metals in aerial part of plant, especially leaves. From the Table 5, it can be observed that the water hyacinth has been successfully tested using wastewater samples from various industries and proved to be a significant low-cost treatment option.

Other applications of water hyacinth

Numerous researchers have been investigated the various beneficial uses of water hyacinth with the intention to promote growth of plant instead of eradicating it from water bodies (Mayo and Hanai 2016). Recent studies indicate that other than phytoremediation, water hyacinth plant can be used for various purposes such as production of ethanol, green manure (compost and mulch), production of biogas, animal feed, and extraction of volatile fatty acids (Uday et al. 2016), as shown in Fig. 4. Ganguly et al. (2012) have presented the mechanism of production of ethanol using lignocellulosic rich plant water hyacinth. Such use could be beneficial in controlling the growth of plant population and providing a simple and low-cost process that is suitable especially in developing countries. Abdel-Sabour (2010), Shoukry (1982), and Osman et al. (1981) described the use of water hyacinth as animal feed for non-ruminant animals. The high water and mineral content in the plant indicates that the plants are appropriate feed for some animals. Also, the dried plant is rich in protein, vitamins, and minerals which can be used as feed for growing poultry and ducks (Dai 2001). Kivaisi et al. (1995) have reported that adding water hyacinth to the duck diet resulted in the increased egg weight and consequently increase in eggshell weight. The water hyacinth contains high concentrations of

Table 3 Bioadsorption of inorganic contaminants from produced water by water hyacinth

S. no.	Parameters	Experimental conditions	Maximum removal efficiency/uptake	Remarks	References
1	Nickel (Ni) and cadmium (Cd)	• Adsorbate: 10 mg/L • Adsorbent: root polymer (0.1 g dry root powder used with polymethyl methacrylate 10 mL), 4 h	Ni (55%) and Cd (70%)	• Adsorption affected by chemical organization of plant roots • Removal rate for Cd (4.9×10^{-5}) was greater than that for Ni (3.6×10^{-5}) in the same time	Elfeky et al. (2013)
2	Arsenic (As)	• Adsorbate: 200 μg/L • Adsorbent: 750 mg dry root • At pH 6, 1 h	• Removal: 93% As(III) and 95% As(V) • Uptake: 50 mg As/g of root	• As in solution after treatment <10 μg/L	Rmalli et al. (2005)
3	Uranium	• Adsorbate: 200 mg/L • Adsorbent: 1 g/L dry root • At pH 5–6, 150 rpm, 24 °C, 1 h	•Removal: 90% • Uptake: 371 mg/g of root in 4 min	• Biosorption influenced by pH, biomass dose, and initial metal concentration in solution • Sorption data obeyed Langmuir isotherm better than Freundlich model	Bhainsa and Sauza (2001)
4	Flouride	• Adsorbate: 2–25 mg/L • Adsorbent: 10 g/L non-carbonized and carbonized plants • At pH 5.5, at temperature range 25–45 °C, 4–16 h	H-type activated carbon at 600 °C (72–98%) and L-type carbon (51–93%)	• Contact time impact on removal efficiency at dose, 10 g/L (34–74% for H-type carbon and 18–64% for L-type carbon with increased contact time from 4 to 16 h) • Percentage of removal higher at 600 compared to 300 °C • Adsorption increases with increasing temperature • Sorption data followed Freundlich model	Sinha et al. (2003)
5	Copper Cu(II)	• Adsorbate: 30 mg/L • Adsorbent: 20 mg roots • 150 rpm, (288–318 K), 1 h	• Removal: >75% • Uptake: 22.7 mg/g	• Sorption kinetics followed pseudo-second-order kinetic model • Sorption data followed Langmuir isotherm	Zheng et al. (2009)

Temperature: °C or K; mixture agitation: rpm; contact time: h or min)

nutrients such as N, P, Mg, Ca, and K; therefore, it can be used for compost and mulch (Mukhopadyay and Hossain 1990). The co-composts of plant with other organic residues (sewage sludge, municipal solid waste, etc.) have been found to increase the yields, protein, and nutrient content of several crops (Singh and Yadav 1986; Gajalakshami et al. 2002). Ganesh et al. (2005) and extracted the volatile fatty acid (VFA) from water hyacinth which has been used as feed supplement in biogas production. The extracted VFA mixed with cow dung slurry could increase the biogas production by 22% than the unfortified slurry. Cheng et al. (2010) reported the mechanism of production of hydrogen using water hyacinth by fermentation technique and found that the 20 g/L of water hyacinth could provide a maximum hydrogen yield of 76.7 mL H_2/g per total volatile solid. Moreover, the water hyacinth is also used for making paper and in furniture industries for making fiber board, yarn, and rope and making baskets and mats (Ndimele and Ndimele 2013).

Problems and prospects

Water hyacinth is called as the most troublesome weed linked to the several problems like obstruction in transport and navigation and clogging of intakes of hydropower, irrigation line, and water supply (Ndimele and Ndimele 2013). The canals and rivers are clogged due to the densely intertwined mat of this weed. The floating water hyacinth mats and stagnant water can serve as a breeding ground for vector organisms carrying malaria, bilharziosis, and filariasis (Abdelhamid and Gabr 1991). Also, such blocked passages could lead to the flooding in the nearby areas. Concern to the fisherman's income, the water hyacinths consume a lot of dissolved oxygen during their decay, which leads to decrease the available oxygen for fishes (Gunnarsson and Petersen 2007). This impact causes the low fish production and loss of fishes, which lower the income of the fisherman and risk to food security. Although this plant has been proved to be a good phytoremediation agent for many toxic pollutants like dichloro diphenyl trichloroethane (DDT), organochlorines, and radioactive ions, the accumulation of these pollutants in the plant biomass might enter in the food chain, which causes the biomagnifications and risk to human health (Weis and Weis 2004). On the other hand, the increased evapo-transpiration due to presence of water hyacinth causes more water loss. The rate of evapo-transpiration has been found to be 1.8 times more than that of evaporation from surface water with no plants (Haider 1989). During decaying, plant biomass releases huge amount of greenhouse gases, which has serious implications in climate change and weathering (Inubushi et al. 2001).

Therefore, to deal with these problems, three methodologies have been adopted to control the growth of the plant. First, the mechanical control method, the plants are removed

Table 4 Bioadsorption of organic contaminants from produced water by water hyacinth

S. no.	Parameters	Experimental conditions	Maximum removal efficiency/uptake	Remarks	References
1	Phenol	• Adsorbate: 50–70 mg/L • Adsorbent: plant ash 0.5 g • At pH (2.5–9), 27 °C, 5 h	Removal: 90–95% Uptake: 30.49 mg/L	• Initial (pH and phenol concentration), contact time, and adsorbent dosage affected adsorption • Sorption followed Langmuir isotherm equation	Uddin et al. (2007)
2	Methylene blue	• Adsorbate: 10–100 mg/1 • Adsorbent: dry root 0.1–1.5 g • At pH 2–10, 60 rpm, 27 °C, 10–120 min	Removal: 95% Uptake: 8.04 mg/g	• Sorption data followed Langmuir and Freundlich models	Soni et al. (2012)
3	Victoria blue	• Adsorbate: 100 mg/L • Adsorbent: 0.1–0.5 g dry root • At pH 2–12, 200 rpm, 2 h	145.4 mg/g	•Uptake rate increased with solution pH increase •Sorption data obeyed Langmuir isotherm	Low et al. (1995)
4	Congo red	• Adsorbate: 25, 50, 75, and 100 mg/L • Adsorbent: 0.1 g acid-activated dry root • At pH 6, 200 rpm, 3 h	46.15 mg/g	• At pH 2–5 and 7–10, adsorption capacity decreased • Sorption data followed Redlich–Peterson isotherm	Rajamohan (2009)
5	Amaranth dye	•Adsorbate: 10–500 mg/L • Leaf particle size ((0.15–0.18 mm)–(1.68–2.0 mm)) • At pH 2, 18 °C, 140 rpm, 72 h	Removal: 98% Uptake: 70 mg/g	• Particle size, solution pH, initial dye concentration, and temperature affected sorption capacity • Biosorption kinetics followed pseudo-second-order rate • Sorption data obeyed Langmuir isotherm, Sips, Redlich–Peterson isotherm, and Radke-Prausnitz and Toth model	Guerrero-Coronilla et al. (2015)
6	Azo and anthraquinone dyes	• Adsorbate: 100 mg/L • Adsorbent: 2.5–15 g/L aminated raw stem • At pH (3–4), 60 min	95%	• Good adsorption from solutions (12% aminated raw plant with sandene)	El Zawahry and Kamel (2004)
7	Crystal violet dyes	• Adsorbate: 20 mg/L • Adsorbent: 1 g/L leaves • At pH 2–10, (30, 40, and 50 °C), 100 min	Removal: 85–98.3% Uptake:116.3 mg/g	• Effective for cationic dye removal	Kaur et al. (2015)
8	Safranin dye	• Adsorbate: 40 mg/L • Adsorbent: 1 g/L • At pH 2–12, (303, 313, and 323 K)	Removal: 85–96% Uptake: 84.8 mg/g	• Dye removal increased with increasing temperature, pH, and adsorbent dose • Sorption data followed Langmuir model	Rani et al. (2015)

Temperature: °C or K; mixture agitation: rpm; contact time: h or min)

Table 5 Phytoremediation of real contaminated wastewater at large-scale application by water hyacinth

S. no.	Wastewater source	Pollutants	Findings	Remarks	References
1	Sewage treatment	BOD, COD, TSS	Removal: COD (90.25%), BOD (96%), TSS (92%) and turbidity (100%) in 4 days	•Capable to produce effluent of very low BOD	Zimmels et al. (2006)
2	Piggery wastes	COD, BOD, total nitrogen (TN), (NH3-N) and total phosphorus (TP)	• 50% reduction in all parameters at 110 kg TN/ha/day and 20 day hydraulic retention time • Adsorption efficiency: 36% upon saturation	• Greater NH_3–N reduction efficiency • Plant straw good phosphorus adsorbent	Costa et al. (2000)
3	Dairy effluent	Temperature, EC, DO, oxidation–reduction potential (ORP), pH, alkalinity, TS, SS, VS, VSS, total COD, soluble COD, Total Kjeldahl Nitrogen (TKN), Na^+, NH4–N, NO3–N, TP, soluble reactive phosphorus (SRP)	Removal: TKN (91.7%), NH4–N (99.6%), TP (98.5%) and SRP (96.5%), EC (89%), TCOD (74%), SCOD (60%), SS (80%), Na^+ (60%)	• Plant productivity in 1:1 dilution of dairy effluent averaged 33.2 g dry weight m^{-2}/days • COD, solid and salinity reductions, water hyacinth performed better than water lettuce and pennywort	Sooknah and Wilkie (2004)
4	Textile effluent	TSS, BOD, DO, COD, nitrate–nitrogen, Cd, and Cu	Removal of TSS (31.71%), BOD (66.98%), DO (42.86%), nitrate (53.64%), Cd (94.87%), Cu (6.64%), COD (80%)	• Efficiently removed cadmium but less efficient for iron and copper	Ajayi and Ogunbayo (2012); Kulkarni et al. (2007)
	Metalurgical	TSS, BOD, DO, nitrate–nitrogen, Cd	Removal of TSS (63.91%), BOD (73.33%), DO (93.33%), nitrate (45.61%), Cd (95.59%)		
	Pharmaceutical	TSS, BOD, DO, nitrate–nitrogen, Cd, Fe	Removal of TSS (63.57%), BOD (52.94%), DO (60%), nitrate (42.42%), Cd (93.55%), Fe (90.91%)		
5	Electroplating (battery, Scooter and Aeronautical industry)	Fe, Cu, Cr, Mn, Cd, Pb	• Battery industry: Cu (315.50 μg/g), Fe (4052.00 μg/g), and Mn (788.42 μg/g) • Scooter industry: 1.3–6.70, 142.03–3196.33, 1.37–24.53, 0.15–3.2, 0.62–5.7, and 0.89–4.2 μg/g for Cu, Fe, Mn, Cd, Cr, and Pb, respectively • Aeronautical industry: 5.56–10.43, 87.41–2025, 3.73–122.85, 1.76–6.3, 2.73–10.87, and 2.78–8.97 μg/g dry weight for Cu, Fe, Mn, Cd, Cr, and Pb, respectively	High accumulation of Fe, Mn, and Cu than *Spirodela polyriza*	Sahu et al. (2007)
6	Dyestuff industries	Total dissolved solid (TDS), pH, conductivity (EC), hardness, DO, BOD, COD, and nitrate–nitrogen and ammonium–nitrogen	• Reduced all physico-chemical and biological parameters to a significant level by 50% in diluted wastewaters • Increased DO concentration	• Plant grown well in 25–50% wastewater • In 75–100% dye wastewater, plants died	Shah et al. (2010)
7	Kraft mill effluent	Color, pH, COD, BOD_5, total phenolic compounds	• Removal: organic matter (46–75%) and total phenolic compounds (11–17%) • Removal: 8.5 and 23.6% of color from 50 and 10% kraft mill effluent, respectively	• No color removal occurred with 100% effluent	Lagos et al. (2009)
8	Palm oil mill effluent	COD, TN, TP	• Removal: 90%		Hadyianto et al. (2013)

Table 5 (continued)

S. no.	Wastewater source	Pollutants	Findings	Remarks	References
				• Two-stage phytoremediation process, a promising method to wastewater treatment	
9	Refinery and petrochemical company	Metals and physico-chemical parameters	• Highest rate of mean reduction for Cd, Hg, Zn, Mn, Pb, and Ag was 99.0, 95.0, 96.3, 100, 99.3, and 94.3%, respectively. • TDS (90%), COD (54.3%), nitrate (86.3%), BOD (13.7%), EC (11%), TSS (55.7%), turbidity (18%), TS (87%), and pH 4%	• Effective treatment	Ugya and Imam (2015)
10	Pulp and paper industry	Zn and Pb	• Uptake: Pb (0.29–1.39 mg/L) and Zn (0.26–1.30 mg/L) after 20 days • Removal: Pb (80.3%) and Zn (73.4%) from 20% effluent	• Effective treatment	Verma et al. (2005)
11	Refinery and petrochemical company	Mn, Zn, Ag, Cd, Hg, and Pb	• The mean biotranslocation factor above one was obtained for each heavy metal	• Effective treatment	Ugya et al. (2015)
12	Gold mine wastewater	Cd, Pb, Ag, Ba, Mo	• Biotranslocation factor was equal to Ba = 0.12 ± 0.03, Mo = 0.85 ± 0.14, Cd = 0.65 ± 0.09, Pb = 0.06 ± 0.01, Ag = 0.18 ± 0.04. •Bio concentration factor was Cd and Ag = 3000, Pb = 18,800 ± 2800, Mo = 24,360 ± 3600, Ba = 10,000	• Effective treatment	Romanova et al. (2016)
13	Mining wastewater	Cu, Mn, Pb, Cd	• Accumulation in leaves: Cu = 6.41–13.5 (mg kg^{-1}), Mn = 62.9–67.9 (mg kg^{-1}), Pb = 3.40–5.06 (mg kg^{-1}), Cd = 0.037–0.13 (mg kg^{-1}) • Bioconcentration factor of Cu = (428–3205), Cd = (7–130), Pb = (242–506), Mn = (285–1100)	• Effective treatment	Prasad and Maiti (2016)

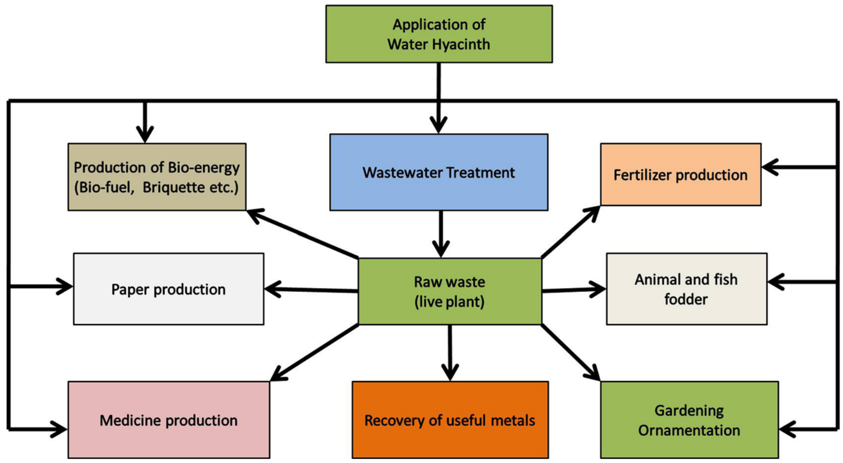

Fig. 4 Various applications of water hyacinth (*Eichhornia crassipes*)

either by hand or by using instruments like pitchforks from the water body and then dumping the collected mass on land to dry or used for making compost and manure (Harley et al. 1997). However, this control method is not always feasible, as it is much expensive, maximum labor intensive, and can cause human health risk. Second is the chemical control method, which includes the use of herbicides like 2-4 D, dalapon, and diquat to eradicate plant by dispersing on them. But this method might damage the biodiversity of other plant communities and imbalance the ecological health of the site (Ndimele and Ndimele 2013). Third, the biological control method, which is a classical technique which involves the use of insects, bacteria, and fungi to remove water hyacinth (Charudattan et al. 1986). The fungal pathogen (*Alternaria eichhorniae*) (Babu et al. 2004) insects *Neochhetina echhornia*, *Neochhetina bruchi*, *Sameodes albiguttalis* (Martyn and Freeman 1978), herbivorous fishes (grass carp and tilipia), duck and geese (Wilson et al. 1977) and turtles, and snails (Rushing 1973) feed on water hyacinth which could be used to control the growth of water hyacinth. Although the biological method control might be a time-taking process, it would be a sustainable and eco-friendly approach. However, the research is still in progress for the improvisation of this method to reduce the treatment cost and duration.

These control strategies have limitations that the most suitable methodology would be often location specific (Malik 2007). The geomorphology of the site, climate and weather pattern, availability of light, and nutrient supply have significant impact on the selection of appropriate control operations (Heard and Winterton 2000). Moreover, the research is required to develop a trustworthy, feasible, and effective technology which could control the growth of water hyacinth in less time and cost without having negative impact on environment. Also, the strategies are required for the recovery of pollutants accumulated in the plant biomass after treatment of wastewater, to prevent the biomagnifications.

Other technologies for contaminant removal vs. water hyacinth

Although various physical, chemical, and biological processes like oxidation and reduction (Bissen and Frimmel 2003), reverse osmosis, electrochemical methods (Pirnie 2000), ion exchange (Wang et al. 2000), chemical precipitation (Ladeira et al. 2002), coagulation (Sancha and Fuentealba 2009) and membrane filtration (Litter et al. 2010), and adsorption (Habuda-Stanić and Nujić 2015) and biological processes like use of terrestrial plants (Mandal et al. 2012), alga, and bacteria (He et al. 2013) are involved as wastewater treatment techniques, the major disadvantages of such technologies entail high cost for production, operation, and maintenance which make them futile to be used at large scale for the treatment of wastewater. The low-cost adsorbents like rice husk, banana and orange peels, neem leaves, modified sawdust, mango seed kernel, pineapple stem, and peanut hulls have been encouraged to be used for treatment nowadays (Annadurai et al. 2002). However, such adsorbent has very low adsorption capacity. Therefore, the research is still required to develop a cost-effective, sustainable, and highly effective technology for treatment of wastewater. Water hyacinth, a notorious weed that vigorously grows, was investigated as a cheap and easily available for effluent treatment by various researchers. However, further studies are still required to investigate the removal efficiency of plant for toxic radioactive metal, hydrocarbons, and pharmaceutical products. Also, research should be conducted to improve the contaminant removal potential of plant by genetic modification, hybridization, and other biotechnological techniques.

Conclusions

Water hyacinth, an invasive aquatic weed, is impossible to eradicate, found in freshwater bodies, though its quest to grow in a nutrient-rich environment has provided an opportunity for its usage in phytoremediation. In the recent advancement of treatment technologies, the plant has been proved to be a good candidate for the removal of contaminants like heavy metals ions, dyes, radio nuclides, and other organic and inorganic contaminants from water at laboratory, pilot, and large industrial scale. In conclusion, water hyacinth has high removal efficiency for heavy metals ions like iron (Fe), zinc (Zn), cadmium (Cd), manganese (Mn), copper (Cu), chromium (Cr), and arsenic (As) and various dyes. The plant grown for phytoaccumulation could be used for production of biogas, and ethanol provides double benefit. Water hyacinth dried body parts as sorbent could provide low-cost treatment of wastewater within less contact time. However, the plant remedial applications need to be investigated more on a large scale. Research should be conducted to enhance its capability to sustain and remove toxic contaminants/nutrients from industrial and domestic wastewater.

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