academicJournals

Vol. 6(10), pp. 267-278, October, 2014
DOI: 10.5897/IJWREE2013.0439
Article Number: 913D51A47722
ISSN 2141-6613

http://www.academicjournals.org/IJWREE

International Journal of Water Resources and Environmental Engineering

Review

Efficacy of phytoremediation potential of aquatic macrophytes for its applicability in treatment wetlands: A review of developments and research

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Received 25 August 2013; Accepted 22 September, 2014

Improving water quality through aquatic macrophytes has made them an essential component in constructed wetland systems (CWS). Experiments worldwide revealed that they do have a role to play in the treatment, but by and large it varied from region to region and species to species. CWS are proven to be an effective, low cost and sustainable alternative to the conventional methods of water treatment. This review included the study of 34 different varieties of macrophytes used for phytoremediation, different types of effluent treated, and experimental mesocosm/ microcosm studies. The ability of macrophytes in nutrient and heavy metal removal are evaluated. In spite of the well established reports indicating the positive role of macrophytes on environmental pollution control, there still exist differences in the performance of several species which are much harder to demonstrate. An effort has been undertaken to review the most researched aquatic macrophytes in the tropical areas, especially the Indian subcontinent so that it can be extended for its application in CWS.

Key words: Constructed wetlands, macrophytes, phytoremediation, water pollution.

INTRODUCTION

The aquatic macrophytes have multiple roles to play in constructed wetlands which have made them an essential component in constructed wetland systems (Brix, 1997; Tanner, 2001; Patel and Kanungo, 2013). Recent studies indicate that the comparison of treatment efficiency of vegetated and unplanted filters is not unanimous, in spite of the majority of the studies showing that systems with plants that achieve higher treatment efficiency (Vymazal, 2011; Odong et al, 2013). Aquatic plant species are very specific for the uptake of nutrients. Thus, the selection of the aquatic plant species is one of the skilled tasks prior to the design of the system (Srivastava, 2008). Presently, the confirmed practices and case studies aid in the selection of aquatic macrophytes rather than assessment of the efficiency of the locally adapted species which are still in the experimental stage in the developing countries (Gopal, 1999; Kivaisi, 2001). The studies in this paper were selected according to the following criteria: 1) studies carried out across India with aquatic macrophyte (floating/ emergent/ submerged) possessing phytoremediation potential. 2) Studies that had different experimental settings (microcosm to full-size constructed wetland systems (CWS) systems are chosen, with or without controls. 3) Our focus was on CWS,

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but we also included studies using other treatment systems as well that may contribute to removal. Here we review the published evidence to ascertain the efficacy of macrophyte species for pollution abatement studied in various parts of the region. We have especially selected the studies that reported the influent and effluent characteristics as they provide the most convincing evidence of removal efficiency of various species. Several studies focussed on different parameters ranging from nutrient removal, heavy metal removal, survivability under stress, dynamics of specific nutrients, etc. Successful phytoremediation requires an integrated approach for each specific site considering right from aquatic macrophyte selection, soil and water management, soil amendments, microflora activity, economics, biomass utilization, social acceptance, economic feasibility, complying with reuse standards and time available to achieve that (Rai, 2009). Besides, this technology is hugely dependant on other factors such as climatic conditions and the criteria for the selection of plant species, that is dictated by their availability, adaptability, pollutant removal capability, tolerance to water saturation, productivity, light demand, etc. It is clear from this review that phytoremediation of aquatic macrophytes can be utilised to remove a wide range of pollutants from wastewater at either a domestic or institutional or community or municipal level. Given the low operation, maintenance, and energy requirements, such systems could well be the systems for achieving sustainable wastewater management in the developing regions of the world.

METHODOLOGY

Thirty-four different varieties of macrophytes were reviewed in this paper which comprises of, 48% emergent, 32% floating and the remaining 20% as submerged species (Figure 1). The studies are selected considering the location as well so that it includes cases covering several states. We included 24 experimental studies that match our criteria, a majority of which were published in the last 5 years. In one case, we treated the two experiments as separate studies that were presented in the same paper (#3 and #4: Table 1 shows the study numbers). Also, we kept two studies as separate even though they have the same plant species, but performed at different times under different experimental conditions (#5 and #6).

The experimental period of the selected studies ranges from 10 days to 2 years. The number of species studied by an author ranges from 1 to 10 as shown in Table 1. Over half of the experiments were performed in microcosm units due to its low cost and ability to replicate and test a large number of macrophytes. However, results from such experiments must consider edge and container effects during interpretation/ scaling up (Tanner, 1994; Fraser and Keddy, 1997). Only two of the studies were carried out at mesocosm level and six were pilot/field scale. The types of wastewater treated ranges from several categories of domestic, industrial effluent and synthetic wastewater. The parameters studied includes several types of nutrients (BOD, COD, N, P, etc..) and heavy metals.

Aquatic macrophytes studied for pollutant removal

Aquatic macrophytes and bacteria in CWS uses the natural processes such as sedimentation, filtration, adsorption, biological degradation, volatilization, photolysis, biotic/abiotic degradation, nitrification/denitrification, microbial uptake, plant uptake, volatilization etc. to treat the wastewater in a controlled environment (Reed, 1995; Cooper et al., 1996; Constructed Wetlands Manual, 1998; Gray, 1999; Rai, 2009). Hammer and Bastian (1989) puts it as “man-made complexes of saturated substrate, emergent and submerged vegetation, animal life and water that simulate natural wetlands for human use and benefits”

In spite of the well established reports indicating the positive role of macrophytes on environmental pollution control, there still exist differences in the performance of several species which are much harder to demonstrate (Brisson and Chazarenc, 2009; Dhote and Dixit, 2009a,b). Plant species diversity enhances the performance of the wetlands (Zhanga et al., 2010).

Various types of wastewater treated using macrophytes

The use of constructed wetlands to treat various wastewaters at both small and large scale is now being recognized across the world due to its good treatment performances and low construction and operating costs (Kadlec et al., 2000; Sonavane, 2008). It has been accepted as a low cost eco-technology alternative to conventional treatment methods, especially beneficial to small communities that cannot afford expensive treatment systems (White, 1995; Green and Upton, 1995; Billore et al., 1999). Some of the earlier experiments were carried out in the early 1950s by Seidel (1961 and 1965) who experimented with macrophytes for treating different kinds of wastewater including phenol, livestock and dairy wastewater. Work done for the past few decades reveal that macrophytes have the potential for purifying different kinds of wastewater. Table 2 shows in detail the types of macrophytes used for the treatment of several types of wastewaters. The influent ranges from domestic wastewater (#5, #12, #13, #24), kitchen wastewater (#2), industrial effluent (heavy metal (#11, #17), battery producing unit (#1), dye wastewater (#21), dairy effluent (#8), coffee processing (#19), metal effluent solution

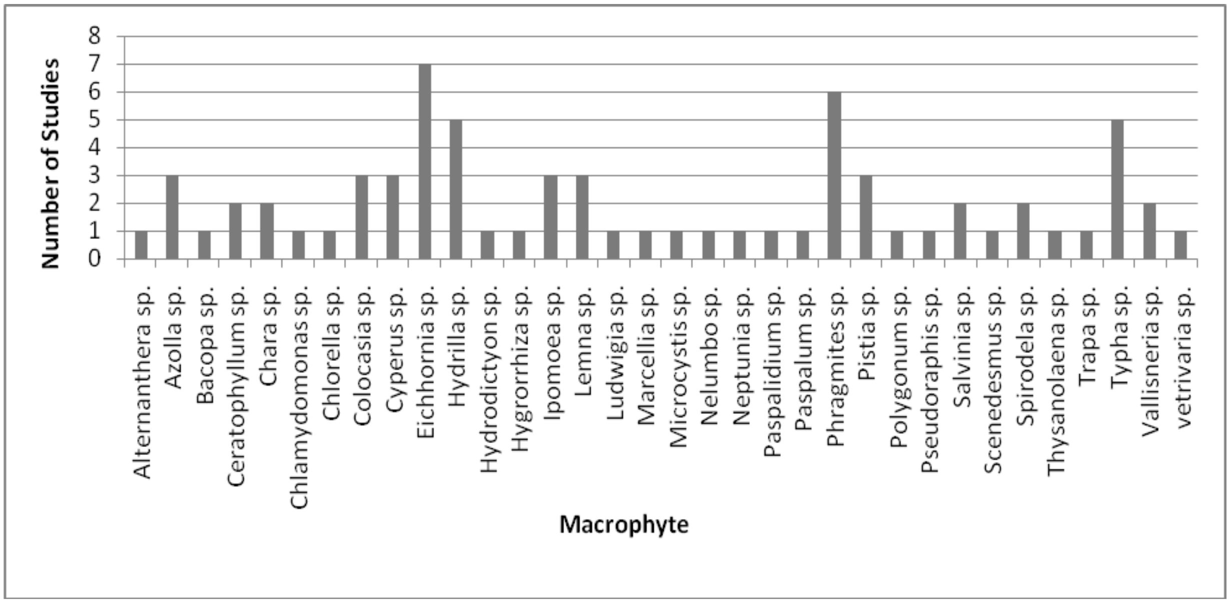

Figure 1. the aquatic macrophytes reviewed as part of this study.

enriched with iron and copper (#10), pulp and paper mill effluent (#14)), synthetic wastewater (soluble reactive phosphorus (#22), diammonium hydrogen phosphate (#20), heavy metal solution with lead and cadmium (#6)) and domestic/ industrial sewage (Table 2).

Nutrient removal by aquatic macrophytes

There have been several attempts by various authors to develop a CWS using aquatic macrophytes to remove nutrients and also comply with the most stringent effluent standards and many such studies clearly demonstrate that the stated objective can be fully met (Platzer, 1996; Laber et al., 1997; Weedon, 2003; Brix and Arias, 2005). Nutrient induced pollution is one of serious concerns in most urban areas of India where groundwater contamination by nutrients such as nitrates is at an unacceptable level in several regions (Gupta, 1981; Trivedy et al., 1988; Sonavane et al., 2008). Sewage contains a large amount of nitrogen and phosphorus apart from other harmful constituents. Increased levels of nutrients in water causes eutrophication thereby rendering them harmful for the aquatic organisms and also depletes the oxygen in water. Table 3 presents the list of macrophytes species studied for nutrient removal at various locations. Currently, systematic collection and remediation of nutrients/heavy metals from waste water are still rare and a large gap exists between the generation and treatment of wastewater (Vasudevan et al., 2011). The options which are available for cost-effective and environmentally compatible sewage treatment include land treatment, waste stabilization ponds, constructed wetlands, duck-weed pond, aerated lagoon, rotating biological contractors, up-flow anaerobic sludge blanket system and root zone treatment (CPCB, 2008). Among these, the constructed wetland systems are still mostly in research phase and its successful implementation is a not as common as seen in the developed world.

In Chennai, Tamil Nadu, Baskar et al. (2009) investigated *Phragmites australis* for the treatment of kitchen wastewater using a pilot-scale, integrated CW with Horizontal Sub-Surface Flow (HSSF) and Vertical Sub-Surface Flow (VSSF) technology for a period of 6 months. The system was designed with 18 m^2 capacity with Hydraulic Retention Time (HRT) of 7 days. On an average, the integrated CWS was found to reduce the concentrations of TSS, TDS, TN, TP, BOD, and COD by 41, 4, 76, 77, 75 and 36%, respectively. Artificial Floating Islands (AFI) vary considerably in their origin, development, species composition, community and physical structure and sustenance even though there are common vegetation elements (John, 2009). Billore et al. (2007) conducted two field-scale experiments using *Phragmites karka*, one through AFI in River Kshipra, Madhya Pradesh and the other through subsurface CW (SSCW) in Ujjain. The former has a size of 200 m^2 while the later 1050 m^2. 0.6 m peanut sized river gravel was used as filter media in the SSCW. On one hand the AFI system reduced the solids (TS and TSS) in the range of 35 to 62% BOD by 37 to 45% and Nitrogen by 16 to 45%. On the other hand, the SSCW system removed TSS with an average of 82% followed by TKN, COD, NH^{4+}-N and BOD ranging from 65-74%. NO^3-N concentration was slightly increased indicating nitrification. Also the DO level

Table 1. Details of the studies selected.

Study #	Authors	Location	No of species	Size and type of CW / other setup *, **	Study period	Control ***
1	Banerjee and Sarker, 1997	Kharagpur, West Bengal	1	Mesocosm, Lab-Scale OP	10 days	Yes
2	Baskar et al., 2009	Chennai, Tamil Nadu	1	Pilot-Scale, Integrated CW with HSSF and VSSF	6 month	No
3	Billore et al., 2007	River Kshipra, Madhya Pradesh	1	Field Scale, AFI	5 month	No
4	Billore et al., 2007	Ujjain, Madhya Pradesh	1	Field Scale, HSSF	12 month	No
5	Bindu et al., 2008	Kottayam, Kerala	1	Microcosm, SSF	20 days	Yes
6	Bindu et al., 2010	Kottayam, Kerala	1	Microcosm, Hydroponic system	20 days	Yes
7	Dhote and Dixit, 2009a,b	Bhopal, Madhya Pradesh	2	Microcosm, Lab-Scale	-	No
8	Dipu et al., 2010	Trivandrum, Kerala	4	Microcosm, Plastic Craits	15 days	Yes
9	Irfan and Shardendu, 2009	Patna, Bihar	1	Microcosm	2 months	No
10	Jain et al., 1989	New Delhi	2	Microcosm, Phytotoron House	14 days	No
11	Kumar et al., 2008	Vidyanagar, Gujarat	7	NA	NA	NA
12	Maheesan et al., 2011	Calicut, Kerala	1	Microcosm, Vertical Intermittent flow CW	90 days	No
13	Patel and Kanungo, 2010	Raipur, Chhattisgarh	1	Microcosm, Lab-Scale	1 year	Yes
14	Prabu and Udayasoorian, 2007	Coimbatore, Tamil Nadu	3	Microcosm, Bench-Scale	2 month	No
15	Prusty et al., 2007	Bharatpur, Rajasthan	7	NA	NA	NA
16	Rai et al., 1995	Lucknow	8	Microcosm, 4 liters(plastic troughs)	15 days	Yes
17	Rai, 2008	Singrauli, Uttar Pradesh	1	Microcosm, 40 liter aquarium	13 days	Yes
18	Rana et al., (2011)	Kalyani, West Bengal	1	Field Scale, Wetland Ponds (2 AP + 2 FP + 2 MP)	1 year	No
19	Selvamurugan et al., 2010	Coimbatore, Tamil Nadu	2	Microcosm	21 days	Yes
20	Sengupta et al., 2004	Bhubaneswar, Orissa	2	Microcosm	12 & 9 weeks	Yes
21	Sharma et al., 2005	Jaipur, Rajasthan	10	Microcosm & Field Scale, Vertical Upflow Wetland	2 years	Yes
22	Srivastava et al., 2009	Lucknow, Uttar Pradesh	7	Mesocosm, Plastic troughs	1 year	No
23	Tripathi and Shukla, 1991	Varanasi, Uttar Pradesh	5	Microcosm, 3 scale aquaculture	6 months	No
24	Vipat et al., 2007	Bhopal, Madhya Pradesh	1	Field Scale, HSSF	18 months	No

*Type of Treatment. AFI: Artificial Floating Island; AP: Anaerobic Pond; CW: Constructed Wetland; FP: Facultative Pond; HSSF: Horizontal Sub-Surface Flow; MP: Maturation Pond; OP: Oxidation Pond; SSF: Sub-Surface Flow; VSSF: Vertical Sub-Surface Flow, **Size of experimental units. Microcosm (columns, buckets): < 0.5 m^2; Mesocosm: 0.51m^2 to 5 m^2; Pilot/ Field Scale: > 5m^2 (Brisson and Chazarenc, 2009), ***Control. Yes: indicates presence of unplanted control.

was increased by 190% indicating an aerobic system.Bindu et al. (2008) conducted a laboratory scale studies using *Colocasia esculenta*. The study used control raceways and gravel (Rock chips of charnackite) based filter media for treating domestic wastewater. The quality of the treated water from plant based system was found to be better than those without plants. Also the species used was found to resist COD concentration as high as 1650 mg/L, indicating the scope for future. polyculture studies along with other native wetland plants Dhote and Dixit (2009a,b)

Table 2. The types of aquatic macrophytes used for the treatment of various wastewaters.

Type of wastewater	Type of macrophyte species*	Study # (Table 1)
Amended water(Containing Soluble Reactive Phosphorus)	E, F	22
Coffee processing wastewater	E	19
Dairy effluent	E, F	8
Domestic wastewater	E	5, 12, 24
Domestic wastewater	F	13
Dye wastewater	E, F, S	21
Heavy metal contaminated wetland	E, F, S	11
Industrial effluent (heavy metal)	F	17
Industrial effluent (battery producing unit)	F	1
Kitchen wastewater	E	2
Metal effluent solution enriched with iron and copper	F	10
Nutrient water (diammonium hydrogen phosphate dahp)	E	20
Pond water contaminated with industrial effluents	E, F, S	16
Pulp and paper mill effluent	E	14
Sewage (domestic wastewater)	E	3
Sewage mixed with industrial effluents	F	23
Sewage water	F	18
	F, S	7
Synthetic heavy metal solution (Pb and Cd)	E	6
Wetland water	E, S	15

* E : Emergent; F : Floating; S : Submergent

Studied the species *Eicchornia crassipes* and *Hydrilla verticillata* in their nutrient removal capabilities. *E. crassipes* is a free floating aquatic plant with abilities to remove nutrients and metals from wastewater (Boyed, 1970; Gupta, 1982; Reed et al., 1995). Growth rates of water hyacinths were found to be influenced by the nutrient composition of the water, plant density, solar radiation, and temperature (Reddy, 1984). *H. verticillata*, a species found to grow well in oxygenated water and has more area for the growth of denitrifying bacteria (Weisner, 1994). This study confirmed its efficiency in reducing COD, TSS, Nitrate, and Phosphate.

A comparative study among *Typha* sp., *Eichhornia* sp., *Salvinia* sp. and *Pistia* sp. was performed by Dipu et al (2010) to treat dairy effluents. The study concluded that emergent species were more efficient than the floating ones and that the *Typha* based system outperformed the systems based on the other three species. Irfan and Shardendu (2009) investigated the dynamics of nitrogen and its uptake and storage by *Pistia stratiotes* under six different experimental conditions with differing nitrogen concentrations. The nitrogen accumulation by *P. stratiotes* was found to be 5 to 15 times higher than the nitrogen content in the water and 2 to 3 times higher than the nitrogen content measured in the soil. Maximum accumulation of nitrogen in *P. stratiotes* was reported to be 15.25 mg g^{-1}. Maheesan et al. (2011) performed an experiment to investigate the treatment efficiency of *Vetrivaria sesmodia* in treating domestic wastewater. A vertical, intermittent flow constructed wetland was designed with gravel and sand as filter media as well as trickling filter. The result was reported to be positive with mean removal efficiency of 89.68% for BOD, 88.66% for COD, 75.56% for SS, 97.13% for NH4-N and 72.74% for Phosphate.

Prabu and Udayasoorian (2007), designed a microcosm scale integrated wetland to investigate the removal of colour, pollutant and phenol from pulp and paper mill effluents using *Phragmites australis, Typha latifolia,* and *Cyperus pangorei*. The pollutant and phenol removal was found to be greater in the system using *Phragmites* sp. Selvamurugan et al. (2010) designed a laboratory scale treatment system using *T. latifolia* and *Colacassia* sp to treat the effluents of coffee processing industry. The results concluded that the performance of *Typha* sp. was better than that of *Colacassia* sp. The percentage pollutant removal of *Typha* sp. was found to be 85.4% for BOD, 78.0% for COD and 57.0% for TS- whereas the percentage removal of *Colacassia* sp. was fair with BOD-81.2%, COD-73.7% and TS-54.8%. Sengupta et al. (2004) investigated the effects of nutrient supply and water depth on nutrient uptake by using two emergent species: *Phragmites karka, Thysanolaena maxima*. The results of the experiment concluded that the uptake of nitrogen and phosphorus increased with water depth and confirms that both the species tolerate flooding and were better suited for treatment of wastewater.

Sharma et al. (2005) conducted a lab and field- scale

Table 3. Macrophyte species studied for nutrient removal at various locations.

Macrophyte	Common name	Parameters studied	Study # (Table 1)
Azolla pinnata	Mosquito Fern, Duckweed Fern, Fairy Moss	pH, Tolerance to dye wastewater	21
Ceratophyllum demersum	Horn Wort, Coontail	pH, Tolerance to dye wastewater	21
Chara najas	Chara	P, NO_3, Ca, K	22
Colcasias sp, *Colocasia esculenta*	Taro, Elephant-Ear	pH, BOD, COD, NO_3^--N, PO_4^--P, EC, TS	5, 6, 19
Cyperus alopecuroides	Foxtail Flat sedge	pH, Tolerance to dye wastewater	21
Cyperus pangorei	Korai Grass	BOD, COD, TSS and Chlorinated Phenol	14
Eichhornia crassipes	Water Hyacinth	pH, Turbidity, EC, TDS, TSS, BOD, COD, TN, N, P, K, Sodium, NNO_3, TS, Tolerance to dye wastewater, SS, PO_4^--P, NO_3^--N, acidity, NH_4^--N, hardness and Coliform bacteria	7, 8, 21, 23
Hydrilla verticillata	Water Thyme, Indian Star-Vine	pH, Turbidity, EC, TDS, TSS, BOD, COD, TN, N, P, K, Na, NO_3, Ca, Tolerance to dye wastewater	7, 15, 21, 22
Ipomoea aquatica	Water-Spinach, White Morning-Glory	P, NO_3, Ca, K, Na	15, 22
Lemna aequinoctialis	lesser duckweed, three-nerved duckweed	pH, Tolerance to dye wastewater	21
Lemna minor L.	Duck weed	Temperature, pH, Turbidity, Salinity, EC, TDS, Alkalinity, Free CO_2, Total CO_2, Chloride, DO, Percentage O_2 Saturation, COD, Total hardness, Calcium hardness, Calcium, Magnesium, Nitrogen in Ammonical, Nitrite, and Nitrate form and Phosphate	13
Ludwigia repens	Creeping Primrose Willow	P, NO_3, Ca, K	22
Marcellia sp.	Goat Weed	P, NO_3, Ca, K	22
Phragmites australis	Common Reed	TSS, TDS, TN, TP, COD, BOD, Chlorinated Phenol	2, 14
Phragmites karka	Elephant Grass , Reed Grass	TDS, TSS, BOD, DO, COD, NH_4^+-N, NO_3^-N, Org-N, TKN, pH, Tolerance to dye wastewater, Coliform Bacteria, Turbidity, TS, Phosphate	3, 4, 20, 21, 24
Pistia stratiotes	Water Lettuce	pH, Turbidity, EC, TDS, TSS, BOD, COD, NNO_3, Na, TS, NO_3^--N, TN, P, NO_3, Ca, K	8, 9, 22
Polygonum barbatum	Joint weed, Smart Weed	pH, Tolerance to dye wastewater	21
Salvinia sp.	Water Fern	pH, Turbidity, EC, TDS, TSS, BOD, COD, NNO_3, Na, TS	8
Spirodela polyrrhiza	Giant Duckweed	pH, Tolerance to dye wastewater	21
Thysanolaena maxima	Broom Grass	Phosphate, N	20
Trapa natans	Water Chestnut	P, NO_3, Ca, K	22
Typha angustata	Cattail Narrow leaved	pH, Tolerance to dye wastewater	21
Typha latifolia	Bulrush, Broad leaf Cattail	pH, Turbidity, EC, TDS, TSS, BOD, COD, NNO_3, Na, TS, Chlorinated Phenol	8, 14, 19
vetrivaria sesmoida	Vetriver Grass	BOD_5, COD, SS, NH_4^-N, PO_4^-P and pH.	12

experiment using 10 species that includes *Azolla pinnata, Ceratophyllum demersum, Cyperus alopecuroides, Eicchornia crassipes, H. verticillata, Lemna aequinoctialis, Phragmites karka, Polygonum barbatum, Spirodela polyrrhiza* and *Typha angustata*. All these species were screened for tolerance towards treating textile dye wastewater released during processing of printed cloth. The study revealed varied tolerance towards dye wastewater. Among the submerged, *Ceratophyllum* was found to be more sensitive and died within 24 h of exposure. The tolerance of free-floating species was found to be *Eicchornia* > *Spirodela* > *Azolla* = *Lemna*. It has been concluded that out of the 4 emergent species, *Phragmites* was the only plant species that survived and performed better than the rest in both the lab and field scale experiments.

Srivastava et al. (2009) studied the removal efficiency of soluble reactive phosphorus (SRP) from amended water by 7 different species of macrophytes (*Marcellia* sp., *P. stratiotes, Ipomoea aquatica, H. verticillata, Trapa natans, Chara najas, Ludwigia repens*). The SRP concentration accumulated by the plant tissue was found in the order *C. najas* > *P. stratiotes* > *H. verticillata* with a value 1.15, 1.05 and 1.04 mg g^{-1} dwt respectively. Though the performance indicates the potential of SRP accumulation by aquatic macrophytes, no single species was reported to have a potential for complete removal of nutrients from wastewater. Vipat et al. (2007) conducted a pilot scale project in Bhopal to study the efficacy of root zone treatment technology for the treatment of domestic waste water. A horizontal subsurface flow constructed wetland measuring 700 m^2 using *P. karka* was designed with no controls. The overall results were positive with percentage removal of Organic Nitrogen - 100%, Coliform Bacteria - 98.7%, Turbidity - 88.4%, TSS - 79.0%, Total Solids - 70.7%, TDS - 71.2%, COD - 77.8 %, TKN -8.9%, BOD - 65.7%, Nitrate Nitrogen - 62% and Ammonium Nitrogen - 53.3%. Lemna minor L., a tiny aquatic plant was studied by Patel and Kanungo (2010) for its potential in the removal of pollutants from domestic wastewater. The results indicate an increase in the value of pH, DO, Percentage O_2 saturation and decrease in value of Alkalinity, CO_2, Chloride, COD, Hardness, Nitrogen and Phosphorus thus indicating an improvement in the overall water quality. Tripathi and Shukla (1991) conducted a microcosm study in three stages that is, a water hyacinth culture followed by an algal culture, and finally a second water hyacinth culture. They experimented with sewage water mixed with industrial effluents by using aquatic macrophyte (*Eichhornia crassipes*) and algae species (*Microcystis aeruginosa, Scenedesmus falcatus, Chlorella vulgaris, Chlamydomonas mirabilis*). The percentage removal of various pollutants were reported as BOD (96.9%), SS (78"1%), total alkalinity (74.6%), PO4--P(89.2%), NO3--N (81.7%), acidity (73.3%), N H4--N (95.1%), COD (77.9%), hardness (68.6%) and coliform bacteria (99.2%). They concluded that the three-stage system of wastewater treatment described is probably the cheapest and most economic method which can be adopted throughout warmer and temperate climates.

Heavy metal phytoremediation using macrophytes

Heavy metal contamination poses many environmental and health problems (Ensley, 2000; Rai, 2009). These contaminants are not only prevalent in mine drainage but also found in storm water, landfill leachate and many other sources. The most commonly used methods of addressing heavy metal pollution are still the extremely costly process of removal. Some of the conventionaltechnologies include ion exchange, nanofiltration, reverse osmosis, chemical precipitation, coagulation etc. which are expensive and not ecofriendly. Economic consideration thus favours the need for an alternative cost-effective technology, as the cleanup of hazardous wastes by conventional technology is expensive (Rai, 2009). Aquatic macrophytes and weeds being hyper accumulators of metals are suitable for phytoremediation (Rai, 2009). The use of plants for remediation of metals offers an attractive alternative because it is solar-driven and can be carried out in situ, minimizing cost and human exposure (Salt et al., 1995, 1998).

Several alternate cost effective technologies are developed to clean up the heavy metals of which phytoremediation seems to be a promising one. Experiments have been done to assess the suitability of local wetland macrophytes for removal of heavy metals. Several macrophytes are screened for their metal accumulating properties for its application in CWs. Table 4 presents the various macrophytes species studied for heavy metal removal from natural and constructed wetlands. There are a number of physical, chemical and microbiological processes involved in the purification, like binding to soils, sedimentation, filtration, adsorption, microbial decomposition, precipitation as insoluble salts, chemical transformation and uptake by bacteria, algae, and plants (Boyd, 1970; Kadlec and Keoleian, 1986; Hiley, 1995; Kadlec and Knight, 1996; Mudgal et al., 2010). Adsorption plays an important role (Mukherjee and Kumar, 2005) in the removal of heavy metals as heavy metals are non-biodegradable and therefore removal of these metals is the only solution for water decontamination (Cheng et al., 2002; Ghosh and Singh, 2005; Bareen et al., 2008).

Several floating, submerged and emergent macrophytes (*Hydrodictyon reticulatum, Spirodela polyrrhiza, Chara corallina, Ceratophyllum demersum, Vallisneria spiralis, Bacopa monnieri, Alternanthera sessilis* and *Hygrorrhiza aristata*) were studied for their potential for heavy metal removal from pond water contaminated with heavy metals under laboratory conditions (Rai et al., 1995). The study focussed on the

Table 4. Macrophyte species studied for heavy metal removal at various locations.

Macrophyte	Common name	Metals studied	Study # (Table 1)
Alternanthera sessilis	Dwarf Copperleaf, alligator weed	Cu, Cr, Fe, Mn, Cd, Pb	16
Azolla pinnata	Mosquito Fern, Duckweed Fern	Fe, Cu, Hg, Cd	10, 17
Bacopa monnieri	Water hyssop, Brahmi	Cu, Cr, Fe, Mn, Cd, Pb	16
Ceratophyllum demersum	Horn Wort, Coontail	Cu, Cr, Fe, Mn, Cd, Pb	16
Chara corallina	Stone Wort, Green Algae	Cu, Cr, Fe, Mn, Cd, Pb	16
Colocasia esculenta	Taro, Elephant-Ear	Pb, Cd	5, 6
Cyperus alopecuroides	Foxtail Flatsedge	Na, K, Ca, Mg, Fe, Mn, Zn, Cu, Ni, Cr, Pb	15
Echinochloa colonum	Shama Millet, Billon Dollar Grass	Cd, Co, Cu, Ni, Pb, Zn	11
Eichhornia crassipes	Water Hyacinth	Cd, Co, Cu, Ni, Pb, Zn	11, 18
Hydrilla verticillata	Water Thyme, Indian Star-Vine	Cd, Co, Cu, Ni, Pb, Zn, Mg, Fe, Mn, Cr	11, 15
Hydrodictyon reticulatum	Water Net	Cu, Cr, Fe, Mn, Cd, Pb	16
Hygrorrhiza aristata	Wild Rice Relatives , Asian water grass	Cu, Cr, Fe, Mn, Cd, Pb	16
Ipomoea aquatica	Water-Spinach, White Morning-Glory	Cd, Co, Cu, Ni, Pb, Zn, Mg, Fe, Mn, Cr	11, 15
Lemna minor l.	Common/Lesser Duckweed	Fe, Cu	10
Nelumbo nucifera	Indian Lotus	Cd, Co, Cu, Ni, Pb, Zn	11
Neptunia oleracea	Water-Mimosa	Na, K, Ca, Mg, Fe, Mn, Zn, Cu, Ni, Cr, Pb	15
Paspalidium punctatum	Bristle Grass	Na, K, Ca, Mg, Fe, Mn, Zn, Cu, Ni, Cr, Pb	15
Paspalum distichum	Knot Grass, Eternity Grass	Na, K, Ca, Mg, Fe, Mn, Zn, Cu, Ni, Cr, Pb	15
Pseudoraphis spinescens	Mud Grass	Na, K, Ca, Mg, Fe, Mn, Zn, Cu, Ni, Cr, Pb	15
Salvinia rotundifolia	Butterfly/ floating/ water fern	Pb	1
Spirodela polyrrhiza	Giant Duckweed	Cu, Cr, Fe, Mn, Cd, Pb	16
Typha angustata	Cattail Narrow leaved	Cd, Co, Cu, Ni, Pb, Zn	11
Vallisneria spiralis	Tape Grass, Eel Grass	Cd, Co, Cu, Ni, Pb, Zn, Cr, Fe, Mn	11, 16

in Pariyej Community Reserve, Gujarat to ascertain the degree of heavy metal (cadmium, cobalt, copper, nickel, lead and zinc) contamination in water and sediments and the role of macrophytes in phytoremediation. *Typha, Eichornia* and *Ipomea* species performed better than the other four species. The results showed the significant differences in accumulation of metals like Zn, Cu and Pb in different plant organs, in roots than that of stems and leaves. Rai (2008) conducted a microcosm study that focused on the phytoremediation of Hg and Cd from industrial effluents from Singrauli Industrial Region using *A. pinnata*. After 13 days of the experiment the concentration of selected heavy metals in the tissues of *A. pinnata* was recorded between 310 and 740 mg Kg^{-1} dry mass, with the highest level found for Cd treatment at 3.0 mg/L^{-1} containing a metal solution. Rana et al. (2011) studied the performance of constructed wetlands in the reduction of cadmium in a sewage treatment cum fish farm at Kalyani, West Bengal.

The free floating, *E. crassipes* was planted in a series of wetland ponds comprising of 2 Anaerobic ponds, 2 Facultative ponds and 2 maturation ponds. The results of the study indicate the percentage reduction in cadmium levels to be 30%. *Salvinia* species exhibit capacity for removing contaminants such as heavy metals, inorganic nutrients, explosives from wastewaters heavy metals such as Cu, Cr, Fe, Mn, Cd and Pb and evaluated eight different aquatic macrophyte species (Table 4: #16). The 15th day observation indicates that Cr level was brought from 4.866 µM to below maximum permissible limits by *C. demersum, H. reticulatum* and *S. polyrrhiza*. Similarly Fe and Mn levels were brought below maximum permissible limits within 15 and 7 days by *C. demersum* and *H. reticulatum* respectively. *B. monnieri* and *H. aristata* decreased Cd levels from 0.155 to 0.009 /µM whereas *S. polyrrhiza* and *H. reticulatum* reduced levels to 0.036 /µM after 15 days of treatment. Over 70% of Pb was removed by *C. demersum, H. aristata* and *H. reticulatum*. Out of the eight macrophytes studied *C. corallina, A. sessilis* and *V. spiralis* accumulated these metals to a lesser extent. *H. aristata*, the emergent *B. monnieri*, the free floating *S. polyrrhiza* and *H. reticulatum* and the rootless submerged plant C. *demersum* have shown promising potential for the removal of heavy metals from diluted wastewaters (Rai et al., 1995). *Azolla pinnata* and *Lemna minor* L. were investigated for iron and copper removal from a metal effluent solution in a microcosm study. Experimental solution contained in a 2 L plastic pots was kept in a phytotoron house and investigated for a period of 14 days. The results indicated that both the species are able to remove iron and copper effectively at low concentration of up to 6 to 8 days of treatment. The uptake potential and survival of *A. pinnata* was found to be higher than that of *L. minor* L. (Jain et al., 1989). Bindu et al. (2010) worked on Taro (*Colocasia esculenta*) a native amphibious plant of Kerala which was found to remove Lead and Cadmium from synthetic heavy metal solution at lower concentrations. In laboratory experiments *C. esculenta* was grown hydroponically in shallow raceways containing Hoagland medium amended with 20, 40, and 60 mg/L^{-1} of Pb and 2, 4, and 6 mg/L^{-1} of Cd. The quality of the treated water from the plant based system was found to be better than the one without plants. The species used was found to be a promising for the remediation of wastewater polluted with lower concentrations of Pb and Cd. The plants remained healthy and survived after 20 days with a concentration of 20 and 40 mg/L^{-1} of Pb and up to 4 mg/L^{-1} of Cd, indicating its suitability as a bio-agent (Bindu et al., 2010).

Prusty et al. (2007) investigated the adsorption of alkali and transition metals in macrophytes of a wetland system comprising of seven different species of emergent and submerged aquatic macrophytes (*Paspalum distichum, Paspalidium punctatum, Cyperus alopecuroides, Pseudoraphis spinescens, Ipomoea aquatica, Neptunia oleracea* and *Hydrilla verticillata*). Plants were analyzed for alkali, alkaline-earth metals (Na, K, Ca and Mg), and transition metals (Fe, Mn, Zn, Cu, Ni, Cr and Pb). In this study Cu, Pb, Cr and Ni were not detectable (ND) in some of the plants. The highest concentration of Pb detected in the study was 0.02 µg/g in *Hydrilla* while it was undetectable in other plants except *Neptunia*. The highest level of Cu found in the macrophyte under the present study was 3.0 µg/g (in *Cyperus*). The Ni level was found at highest concentration in *Hydrilla* (0.2 µg/g). In all the macrophyte species, Mn was found to be in highest concentration followed by Fe and Zn. K followed Zn in all the plants except *Cyperus*. The overall study indicates that the alkali metals are restricted while the transitional elements are considerably accumulated. In the present investigation, all the metals were within the general concentration range. Nevertheless, there is the likelihood of elevated levels in the root parts.

Seven native aquatic macrophyte species (*Echinochloa colonum, Ipomoea aquatica, Eicchornia crassipes, Typha angustata, Hydrilla verticillata, Nelumbo nucifera* and *Vallisneria spiralis*) were investigated by Kumar et al. (2008) (Dhir, 2009). The role of *Salvinia rotundifolia* in remediating lead from Industrial (Battery producing unit) waste water was investigated by Banerjee and Sarker (1997). The results indicated over 95% removal of lead from the waste water by *Salvinia* sp.

While several aquatic macrophytes have shown the ability to hyper-accumulate metals from the wastewater, they are still vulnerable to the toxicants present in such environment which limit the plant growth and ability to hyper-accumulate. This can be overcome by adding endophytes (bacteria that favours growth) to the system which significantly improve the ability to phytoremediate and also favours the plant growth (Glick and Stearns, 2011). However, this process does not guarantee the complete remediation of the metals. This is because, on one hand, if plants are not harvested on time, they may die off and release the metals back to the water and on the other hand if they are harvested and not disposed off safely then it will only lead to a transfer of the problem to a different site. Through some species like *A. pinnata* can be used as a bio-fertilizer after some mild chemical treatment for metal removal, in general, they cannot be used as a bio-fertilizer or animal feed. Due to this, the safest option of disposal would be to produce biogas (Rai and Tripathi, 2007; Rai, 2007, 2009).

CONCLUSION AND RECOMMENDATION

This paper reviewed various studies in India and elaborated the experiences in using aquatic macrophytes for water treatment by delineating some of the key treatment efficiency parameters and performance issues. Experiences reveal that plants indeed play a vital role and improve the overall treatment efficiency. From this review, it is also clear that CWS systems utilizing the phytoremediation capabilities of aquatic macrophytes can be designed and operated to remove a wide range of pollutants from wastewater. Given the low operation, maintenance, and energy requirements, constructed wetlands could well be the systems for achieving sustainable wastewater management at all levels.

It was found that the most frequently used plant among the studies reviewed is *Eichhornia* sp. (Water Hyacinth). Species of the genera *Phragmites, Hydrilla* and *Typha* sp. are the other frequently used ones followed by *Azolla, Colocasia, Cyperus, Ipomoea, Lemna* and *Pistia sp.* Based on the studies reviewed, kitchen wastewater seems not to be suited for phytoremediation due to relatively high pollutant load. *C. esculenta* is found to resist high COD concentration and thus can be used in situations containing high COD in the influent. In general, the emergent species outperformed the submergent species which might be accredited to their massive growth rates. *Typha* sp. was found to be better suited to treat dairy and coffee processing effluents whereas *Phragmites* sp. was found to be better suited to treat domestic, textile dye wastewater, pulp and paper mill effluents. Among the free-floating species, *Eicchornia* and *Ceratophyllum* was found to be better suited to treat textile dye wastewater. Treatment using multiple stages was found to be better than single stage treatment. Among the heavy metals remediation, *C. demersum* was found to be better suited to treat wastewater contaminated with heavy metals such as Cu, Cr, Fe, Mn and Pb. On the other hand, *H. aristata* and *C. esculenta* are found to be better suited to treat wastewaters contaminated with Pb and Cd. However, proper and timely harvesting of plants is very important so as not to release back the contaminants to the wetland through decay. The safest option of disposal in this case would be to produce biogas rather than using as fodder.

It was also found that CWS can be applied either at a domestic scale to treat domestic wastewater (Vipat, 2007; Bindu et al., 2008; Maheesan et al., 2011) or applied by small communities (Green and Upton, 1995; Laber et al., 1999) or serve as an economical alternative to secondary treatment of stabilization pond effluent, the most common treatment system in use in economically poor countries (Kivaisi, 2001; Fenxia and Ying, 2009). Though CWS has been widely used for wastewater treatment across the world, but to date, the technology has been largely ignored or adequate research is unavailable in developing countries where effective, low cost wastewater treatment strategies are needed the most (Kivaisi, 2001; Trivedy, 2007). In developing countries where at present only less than 30% of wastewater is treated due to the high costs incurred by the conventional wastewater treatment methods (Sonavane et al., 2008), there is a critical need for cost-effective, long-term, wastewater treatment technologies to deliver public health and environmental protection (Sundaravadivel and Vigneswaran, 2010). Most importantly, significant work is required on the various methods of handling the biomass generated by the macrophytes (Srivastav, 1993).

CWS being an attractive alternative to the conventional methods for the treatment of various types of wastewater, the potential for its application is enormous in the warm tropical and subtropical climates which aides in higher biological activity resulting in better performance. In spite of the encouraging results of the various studies reviewed, there are quite a few limitations noticed in several of the studies. Most of the systems are microcosm scale experiments; hence the operational/performance data obtained may not be of much use in the implementation of full-scale units. The studies are primarily focussed on monoculture experiments which even though useful, cannot rule out the efficacy of poly-culture experiments as the latter are found to be better in overall performance and seemed to provide the best and most consistent treatment for all wastewater parameters, while being least susceptible to seasonal variations (Karathanasis, 2003; Debing, 2009).

The study period should also be sufficiently long enough to get a more reliable and consistent data. Even though CW has a low operational and maintenance cost (Juwarkar et al., 1995), its practical application in the developing countries is not widespread. This is primarily due to lack of sufficient data, awareness and expertise. However, there are certain drawbacks of such systems, especially its adaptation in the developing countries which includes requirement of large land area, lack of published knowledge on native macrophyte species (Gopal, 1999), diverse characteristics of wastewater, lack of design principles and implementation methodology and cases of economic feasibility for large scale implementation (Batchelor and Loots, 1997; Kadlec and Knight, 1996). Moreover, the process dynamics of CWS are yet to be clearly understood combined with other practical limitations like mosquitoes/ pest problems, steep topography and a high water table which restricts the adoption of these systems (Sundaravadivel and Vigneswaran, 2010).

In the future, it is conceivable that an integrated, multidisciplinary and local research effort is required to achieve a greater success in the application of phytoremediation techniques for treating wastewater.

Conflict of Interest

The authors have not declared any conflict of interest.

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